



Advancements in Scale Resolving Simulations for High-Lift Predictions and Jet Aeroacoustics

Jeffrey Housman, Emre Sozer, Aditya Ghate, Oliver Browne,
Gerrit-Daniel Stich, Jared Duensing

Launch Ascent and Vehicle Aerodynamics (LAVA) team

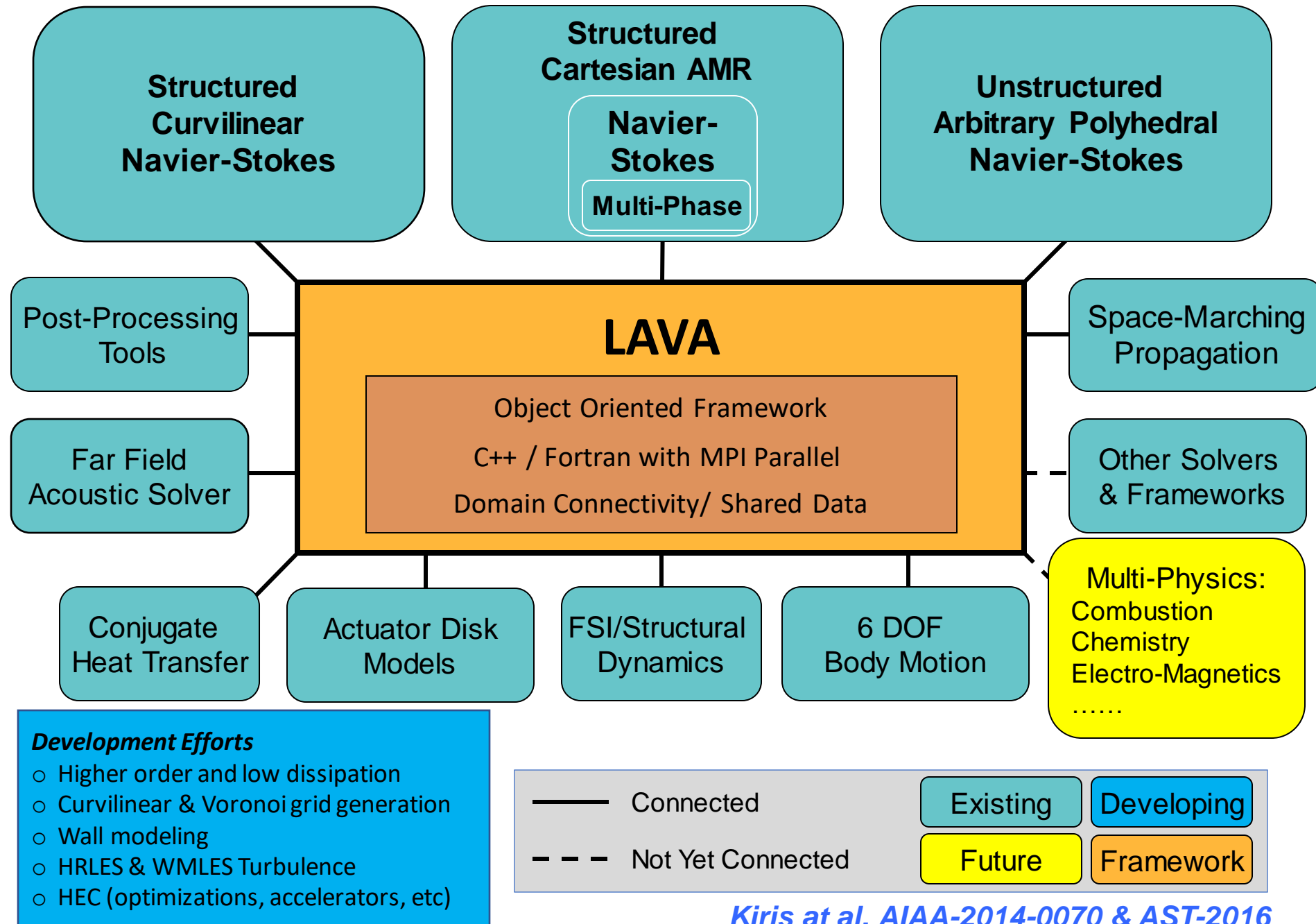
Computational Aerosciences Branch (TNA)

NASA Ames Research Center

NASA/Gulfstream TIM, NASA Langley Research Center

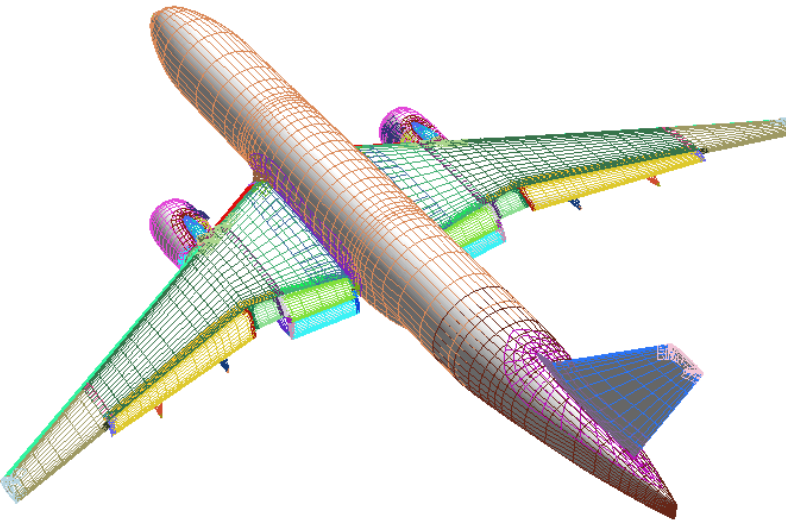
February 7th, 2023

Launch, Ascent, and Vehicle Aerodynamics (LAVA) Framework



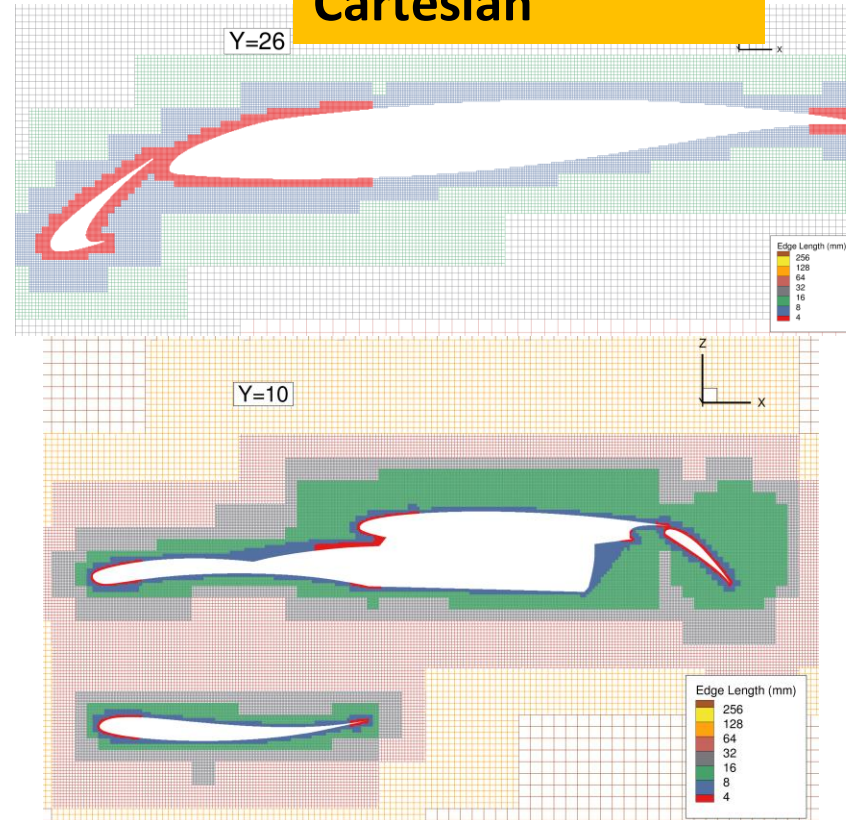
CFD Grid Paradigms

Structured Curvilinear



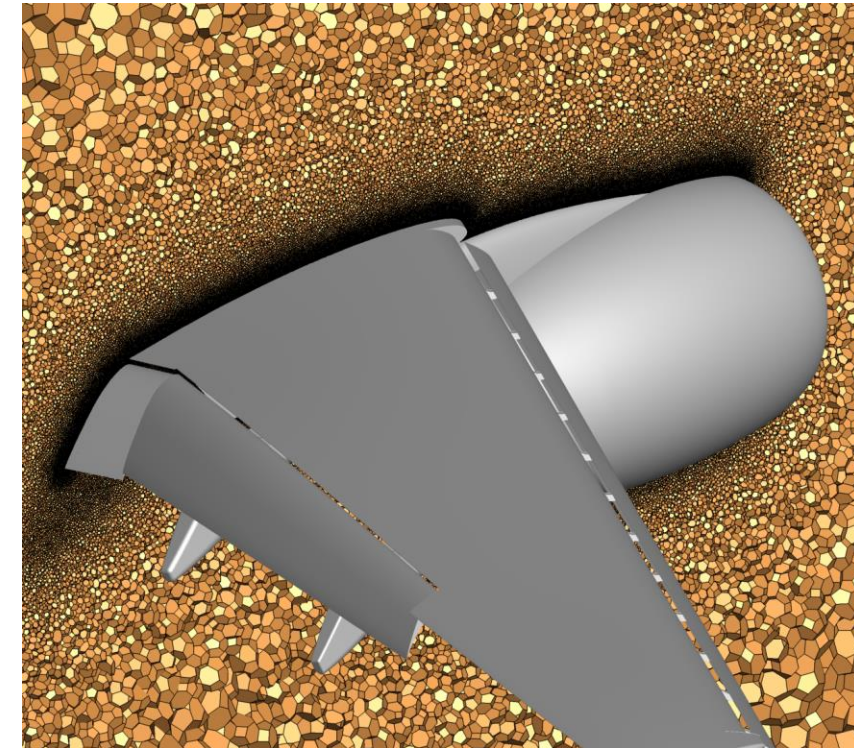
- High quality body fitted grids
- Low computational cost
- Reliable higher order methods
- Grid generation largely manual and time consuming

Cartesian



- Automatic volume grid generation
- High-order methods are efficient and mature
- Isotropic grid cells nonideal for boundary layer resolution
- Success of wall modeling is a key

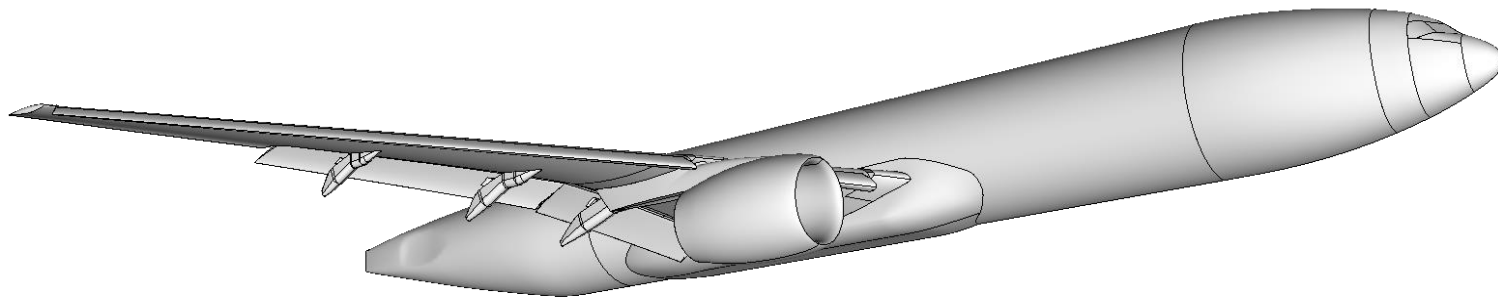
Unstructured



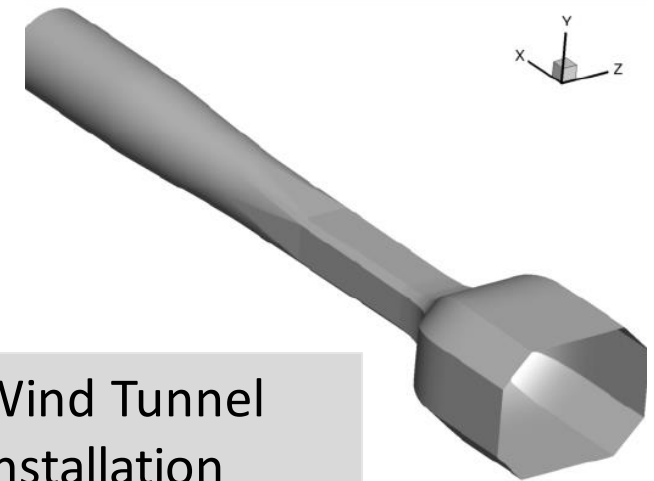
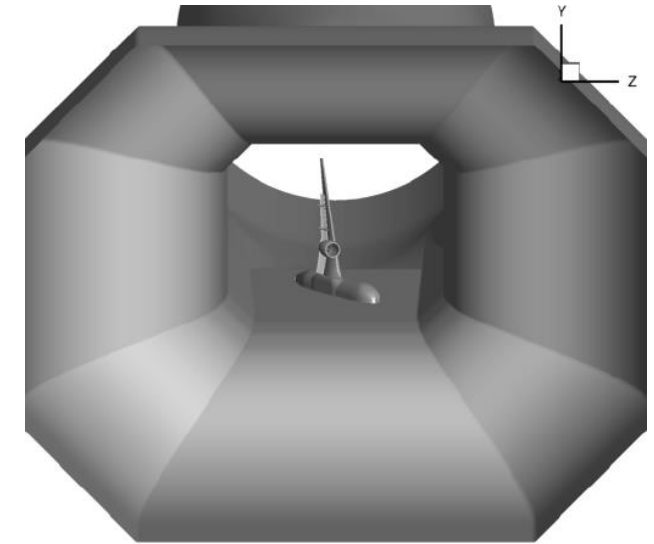
- Partially automated grid generation
- Body fitted grids
- Grid quality can be challenging
- Computational cost and memory requirements
- Higher order methods yet to fully mature

High-Lift Common Research Model: $C_{L_{max}}$ Prediction

- Participated the AIAA High-Lift Prediction Workshop-4 (HLPW4) RANS, Wall-Modeled Large Eddy Simulation (WMLES) and Hybrid RANS/LES (HLES) Technology Focus Groups.
- Extensive validation studies were performed for Free Air and Wind Tunnel installed case
- 5 AIAA papers have been published from LAVA



Free Air



Wind Tunnel
Installation



High-Lift Common Research Model: $C_{L_{\max}}$ Prediction

- ***“High-Lift Common Research Model: RANS, HRLES and WMLES perspectives for $C_{L_{\max}}$ prediction using LAVA”*** by Kiris et. al. AIAA Scitech Forum 2022 DOI: [10.2514/6.2022-1554](https://doi.org/10.2514/6.2022-1554)
- ***“A Reynolds-Averaged Navier-Stokes Perspective for the High Lift-Common Research Model Using the LAVA”*** by Duensing et. al. AIAA Aviation Forum 2022. DOI: [10.2514/6.2022-3742](https://doi.org/10.2514/6.2022-3742) and AMS Seminar <https://www.nas.nasa.gov/pubs/ams/2022/05-26-22.html>
- ***“A Hybrid RANS-LES Perspective for the High Lift-Common Research Model Using the LAVA”*** by Browne et. al. AIAA Aviation 2022 Forum . DOI: [10.2514/6.2022-3523](https://doi.org/10.2514/6.2022-3523) and AMS Seminar <https://www.nas.nasa.gov/pubs/ams/2022/06-02-22.html>
- ***“A Wall Modeled LES Perspective for the High Lift-Common Research Model Using the LAVA”*** by Ghate et. al. AIAA Aviation 2022 Forum . DOI: [10.2514/6.2022-3434](https://doi.org/10.2514/6.2022-3434) and AMS Seminar <https://www.nas.nasa.gov/pubs/ams/2022/06-09-22.html>
- **“Investigation of a Hybrid RANS-LES Approach for $C_{L_{\max}}$ Prediction on NASA High Lift Common Research Model”** by Browne et. al. Accepted for publication in AIAA Journal

CRM-HL at the stalled state

Particle traces colored by Mach number
Curvilinear WMLES at the post CLmax Stalled State
1.1 Billion point grids
Timestep Size: $3.4\mu s$
Video Credit: Timothy Sandstrom

Smallest Geometric Length Scale: Approx. 2.5mm (blunt trailing edges)

Smallest Time-Scale: Approx. $600\mu s$
(shedding time-scale, $St=0.2$, for slat brackets)

Largest Time-Scale: At least 1.5s
Largest Relevant Length Scale: At least 7m
(size of inboard separated region)

Peak Mach (mean-flow) Number: Approaching $M = 1$ (outboard slats)
Peak Suction: $c_p \approx -15$ (outboard slats)



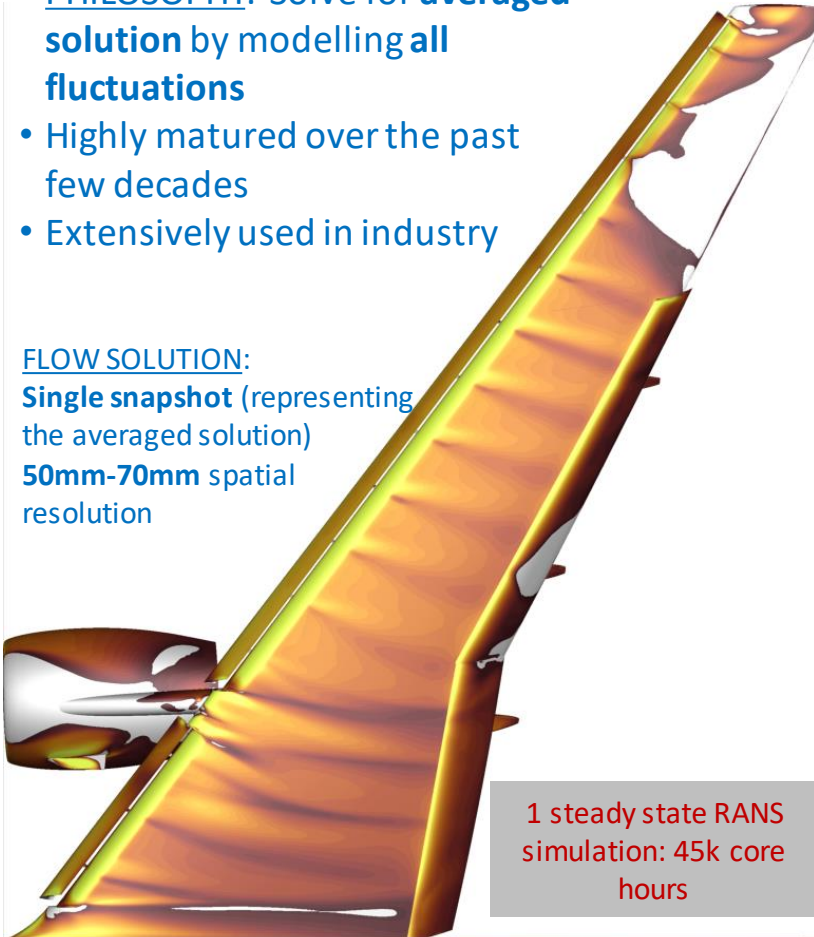
CFD Turbulence Closure Methods

REYNOLDS AVERAGED NAVIER STOKES (RANS)

1980s - Present

- PHILOSOPHY: Solve for **averaged solution** by modelling **all fluctuations**
- Highly matured over the past few decades
- Extensively used in industry

FLOW SOLUTION:
Single snapshot (representing the averaged solution)
50mm-70mm spatial resolution



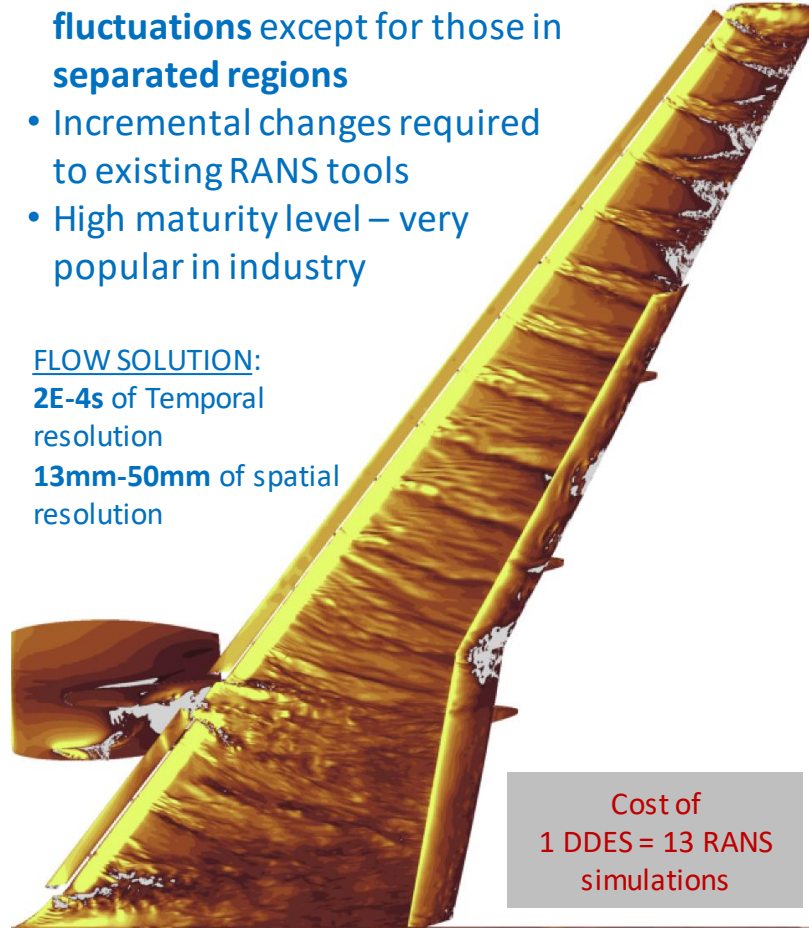
1 steady state RANS simulation: 45k core hours

DELAYED DETACHED EDDY SIMULATIONS (DDES)

1990s - Present

- PHILOSOPHY: **Model all fluctuations** except for those in **separated regions**
- Incremental changes required to existing RANS tools
- High maturity level – very popular in industry

FLOW SOLUTION:
2E-4s of Temporal resolution
13mm-50mm of spatial resolution



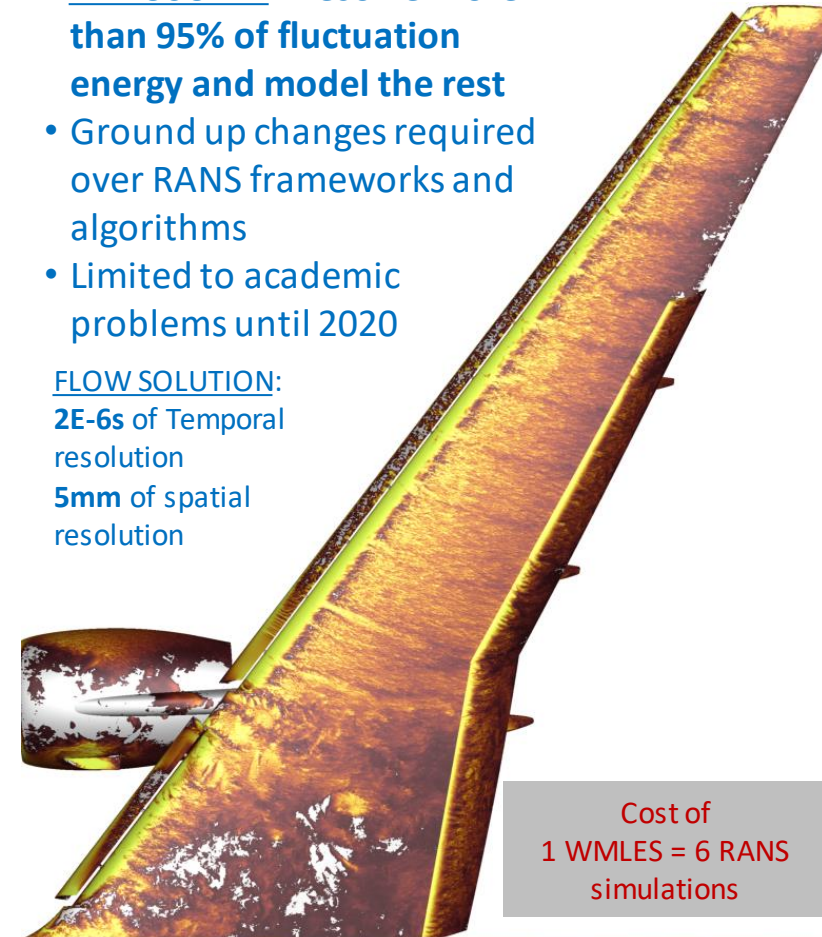
Cost of 1 DDES = 13 RANS simulations

LARGE EDDY SIMULATIONS (WMLES)

2020 - Present

- PHILOSOPHY: **Resolve more than 95% of fluctuation energy and model the rest**
- Ground up changes required over RANS frameworks and algorithms
- Limited to academic problems until 2020

FLOW SOLUTION:
2E-6s of Temporal resolution
5mm of spatial resolution



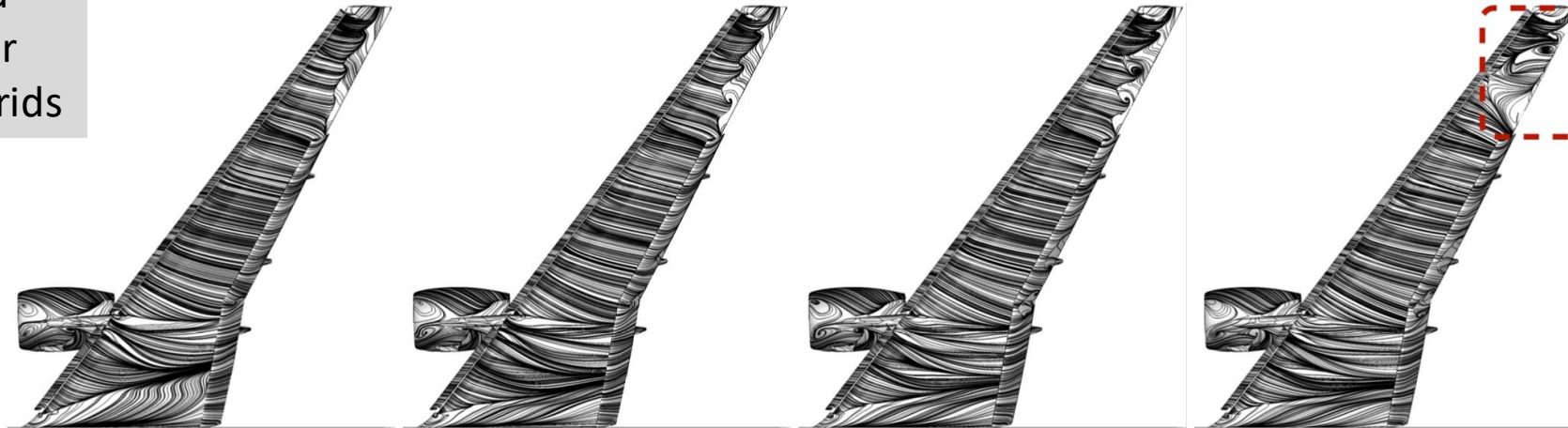
Cost of 1 WMLES = 6 RANS simulations

Problems with RANS- High-Lift



Excess Spurious Separation on Inboard and Outboard Wing:

Structured
Curvilinear
Overset Grids



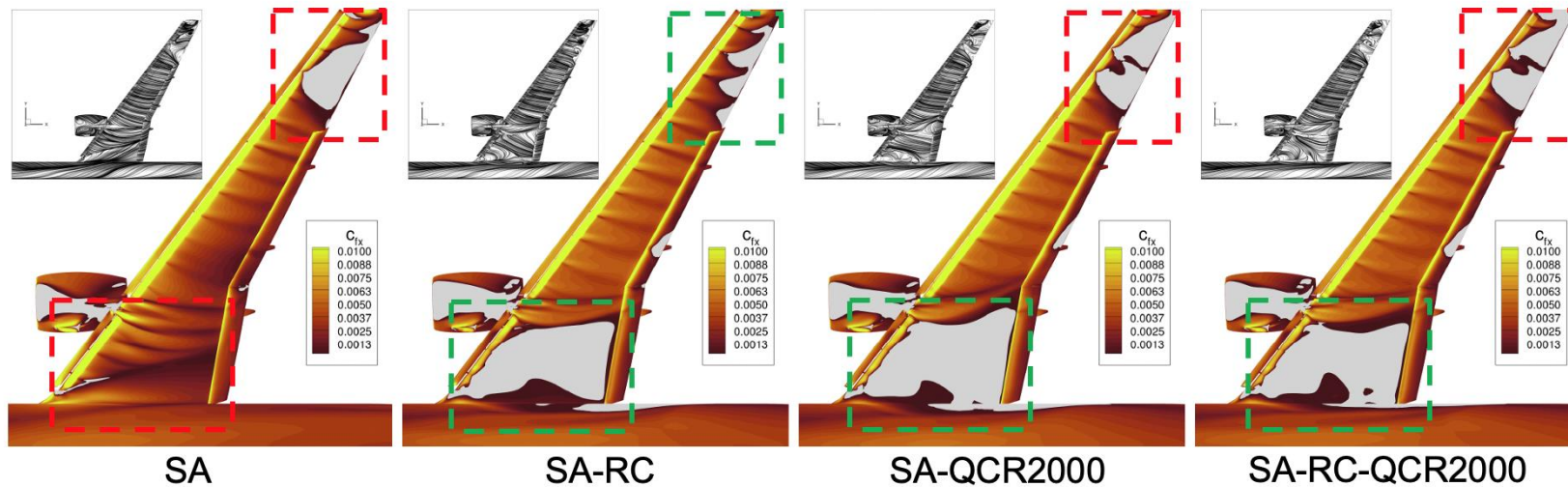
(e) $\alpha = 19.57^\circ$, Grid R-A

(f) $\alpha = 19.57^\circ$, Grid R-B

(g) $\alpha = 19.57^\circ$, Grid R-C

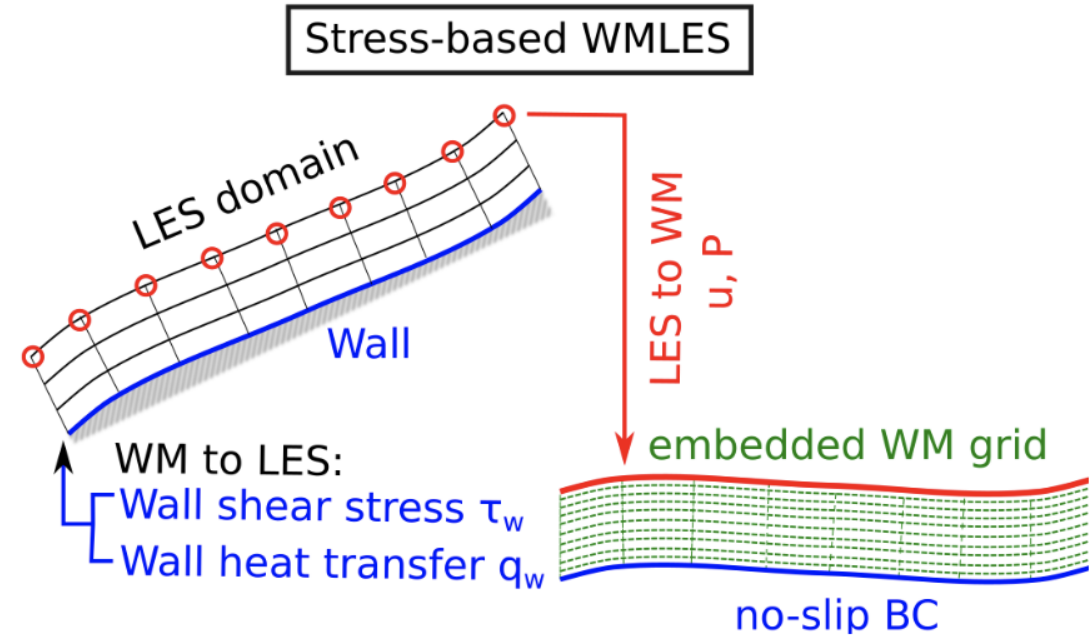
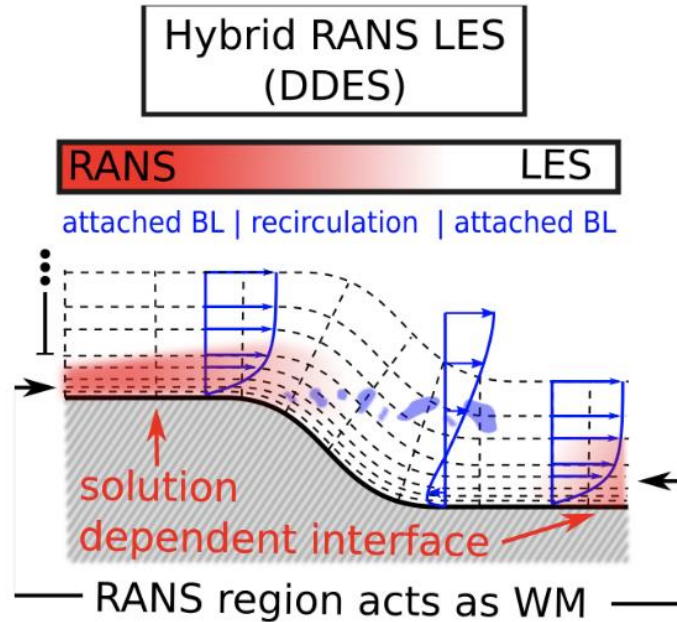
(h) $\alpha = 19.57^\circ$, Grid R-D

Solution worsens
with grid
refinement -
baseline SA model



Solution worsens
with SA corrections

Turbulence Closure in Scale Resolving Simulations



Problems with the method:

- No universally successful choice of a “shielding function” – what all should this be a function of?
- Unclear if the “switch-to-LES” philosophy is valid for smooth body separation
- $y^+ \approx 1$ grid makes having LES-appropriate spanwise and streamwise spacings difficult – anisotropic grids are expensive in time-accurate compressible flow formulations (implicit time-stepping)

Problems with the method:

- Equilibrium assumption may not always apply – non-equilibrium models do not scale to complex geometries
- Correct scaling of computational cost with Re is not clear – academic scaling arguments appear to be more restrictive than experience
- Low-Reynolds numbers – Laminar boundary layers cannot be represented unless anisotropic grids are used; non-empirical model for bypass transition not known.

HRLES (DDES): Should the Mesh Differ from RANS?



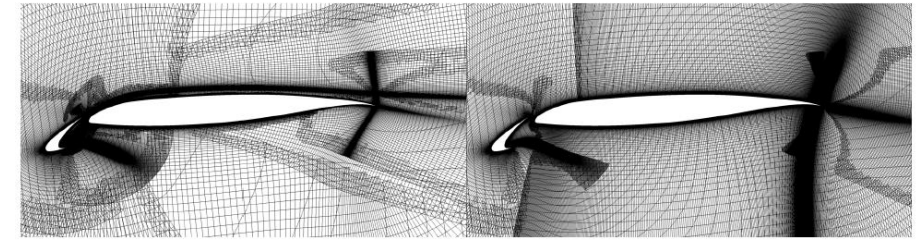
Typical community practice: RANS grids are utilized for HRLES scale-resolving simulations is a common mistake, no universal best practices exist?

best practice grid is Grid H-D and non-dimensional $\Delta t = 1.95e-3$

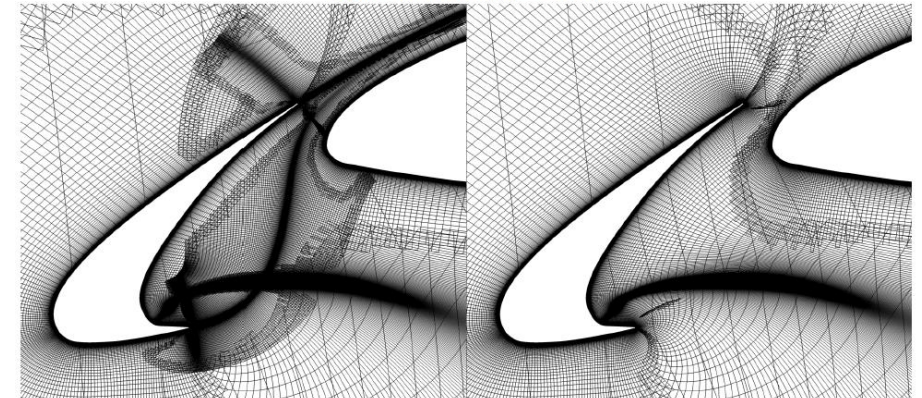
Name	Solve Points	Target y^+	Max Stretching Ratio	Comments
Grid R-C	224M	1.0	1.10	
Grid H-A	365M	1.0	1.10	inboard + outboard refinement
Grid H-B	325M	1.0	1.10	modified slat wake grid + outboard refinement
Grid H-C	421M	1.0	1.10	outboard refinement
Grid H-D	571M	1.0	1.10	inboard + midboard + nacelle refinement

RANS Grid R-C

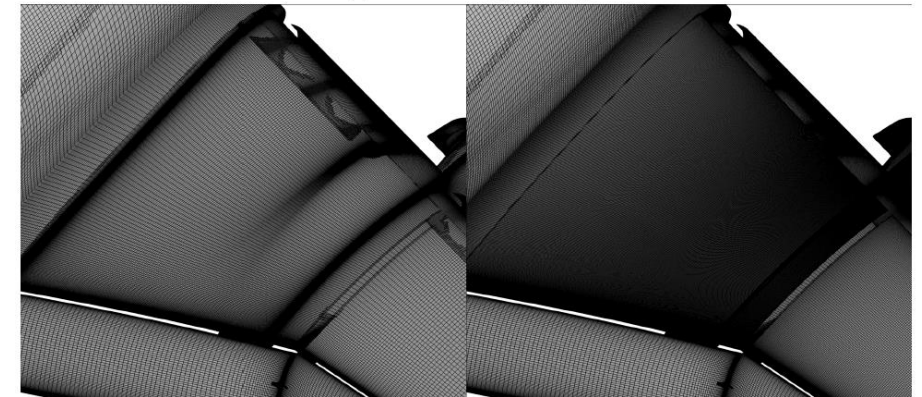
HRLES Grid H-D



(a) Outboard wing ($y = 24$ m.)



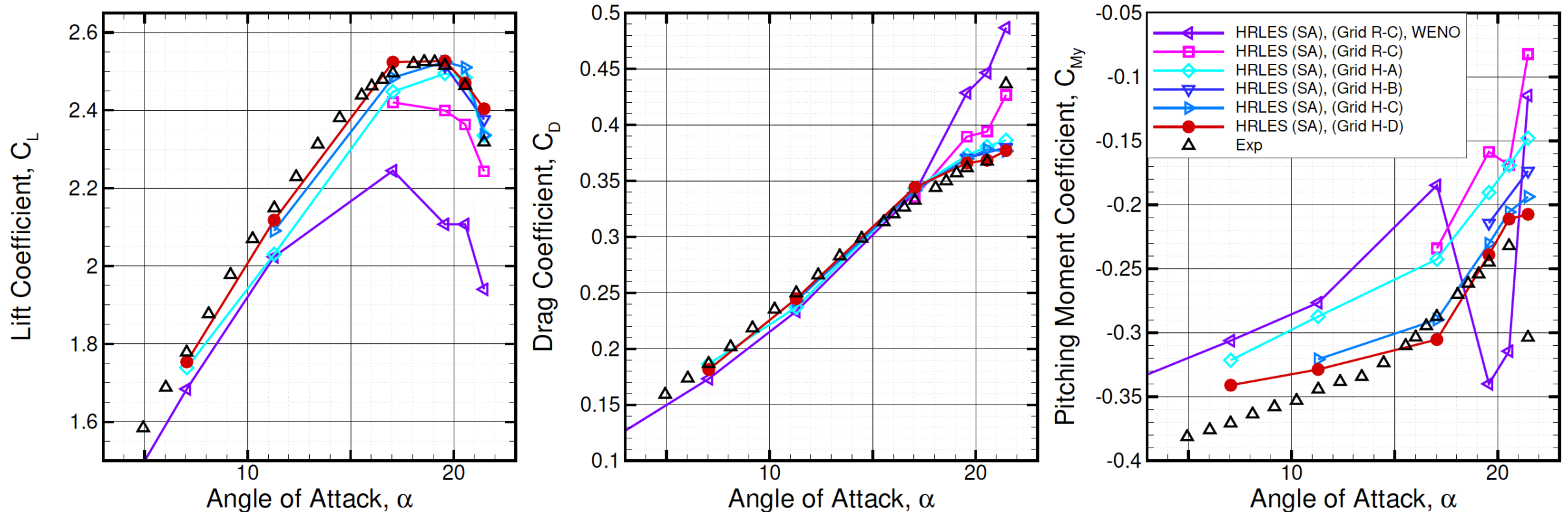
(b) Slat element ($y = 15$ m.)



(c) Inboard wing upper surface

DDES: Effect of Grid Resolution

Aerodynamic loads for various grid levels and numerics computed with HRLES compared with corrected experimental results. Best practice HRLES is shown in red.

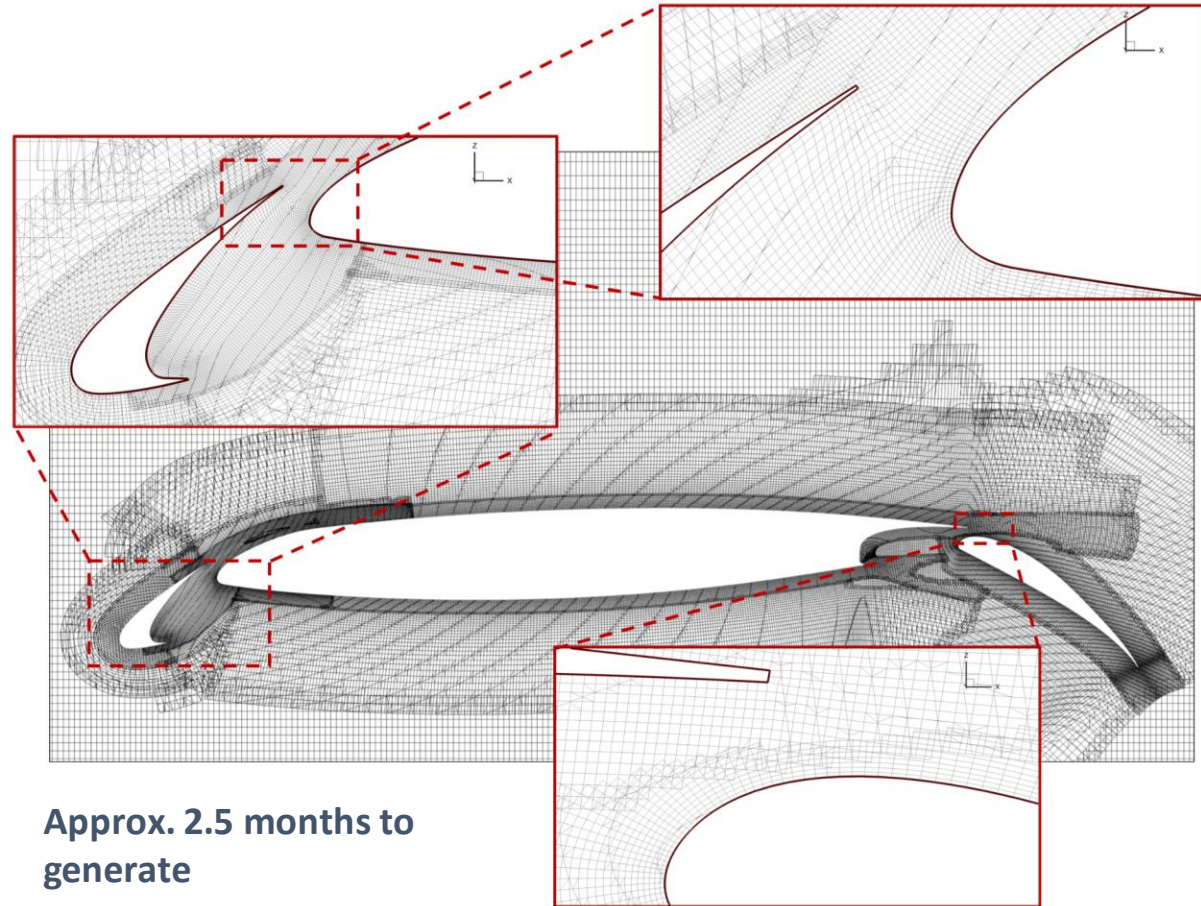


Note: pitch break not guaranteed in free air case

Wall Modeled Large Eddy Simulations (WMLES)

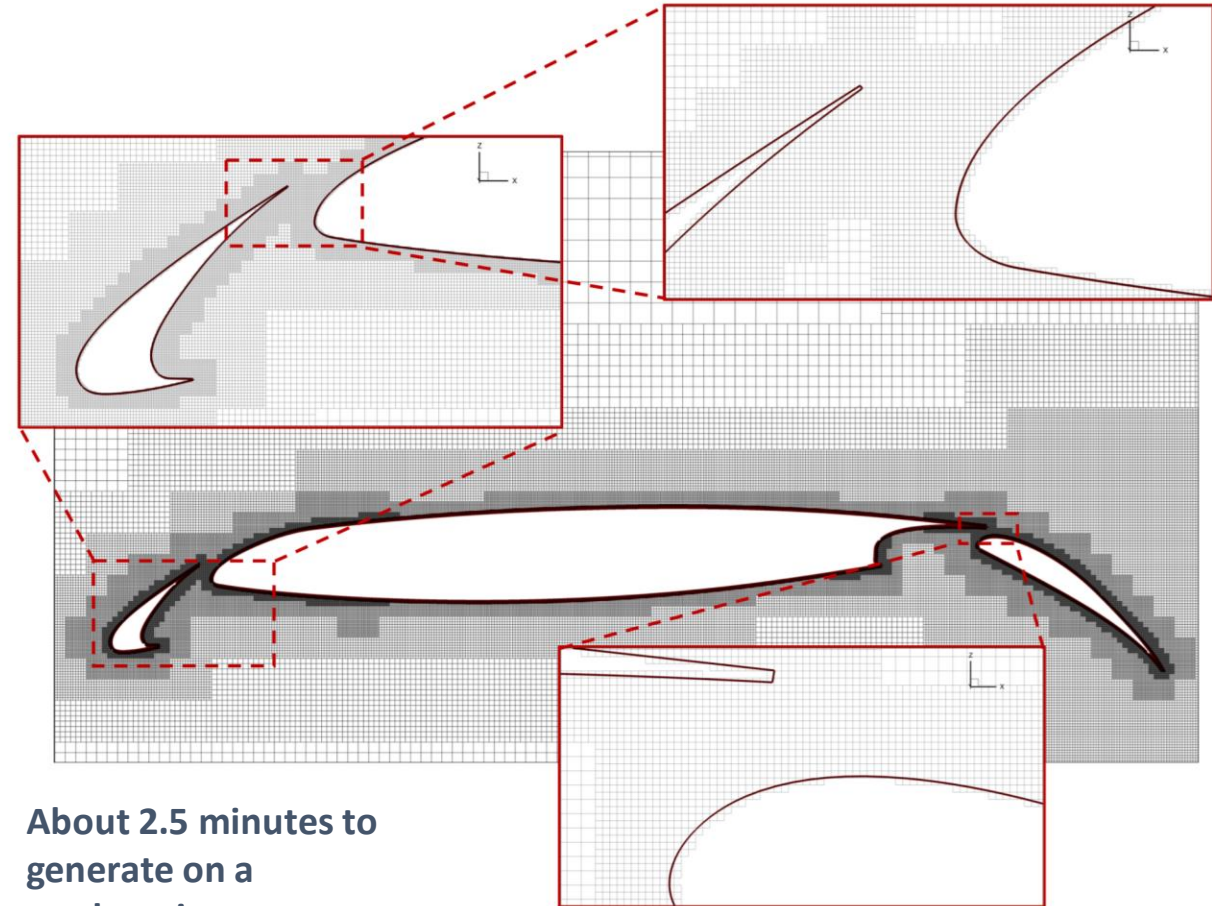


What is the correct grid paradigm?



Approx. 2.5 months to generate

(a) Curvilinear Overset Topology



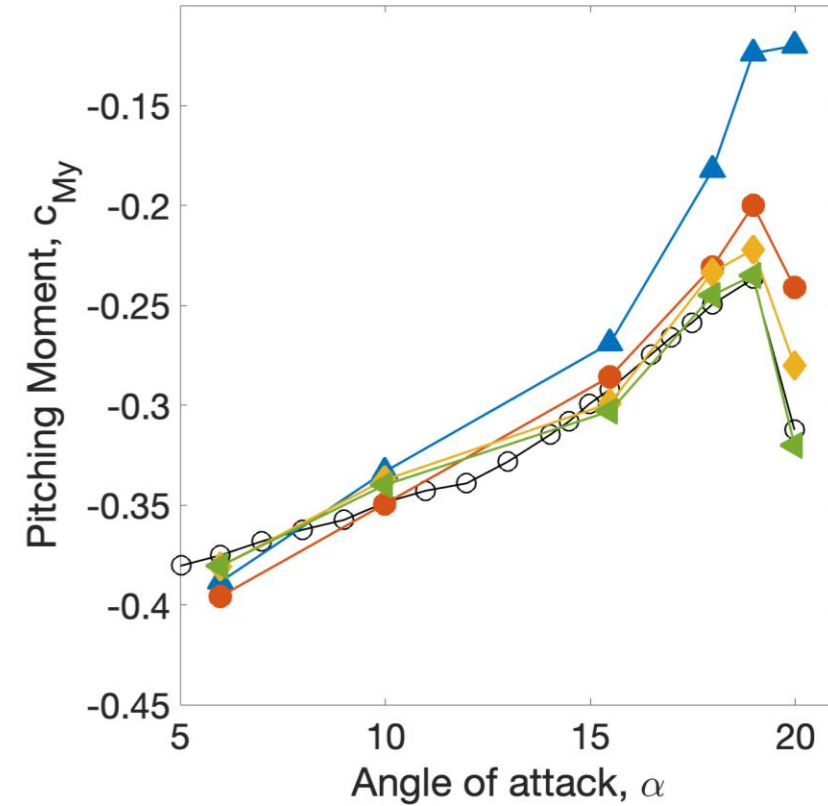
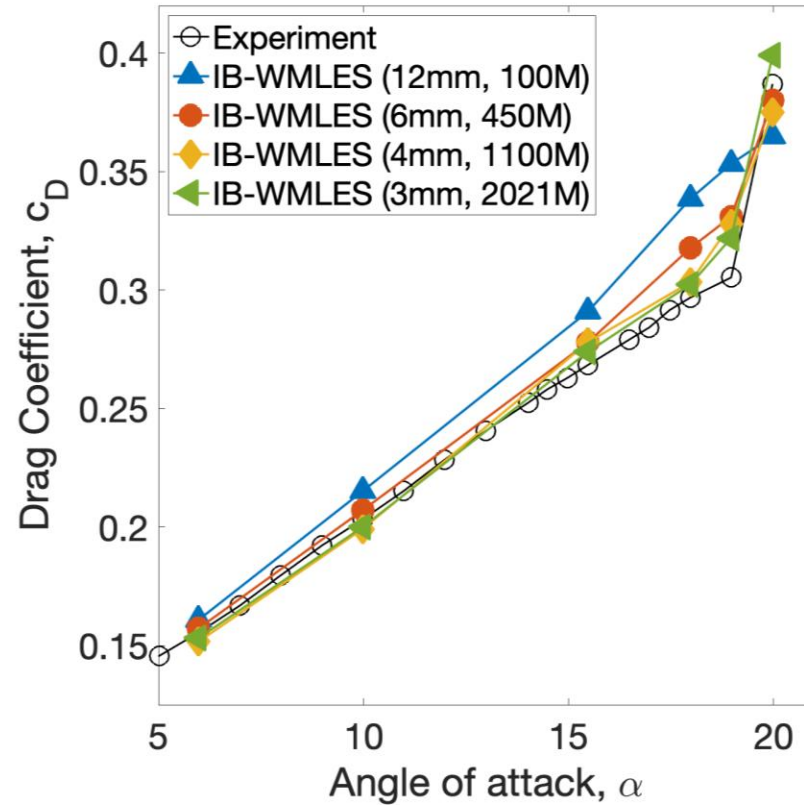
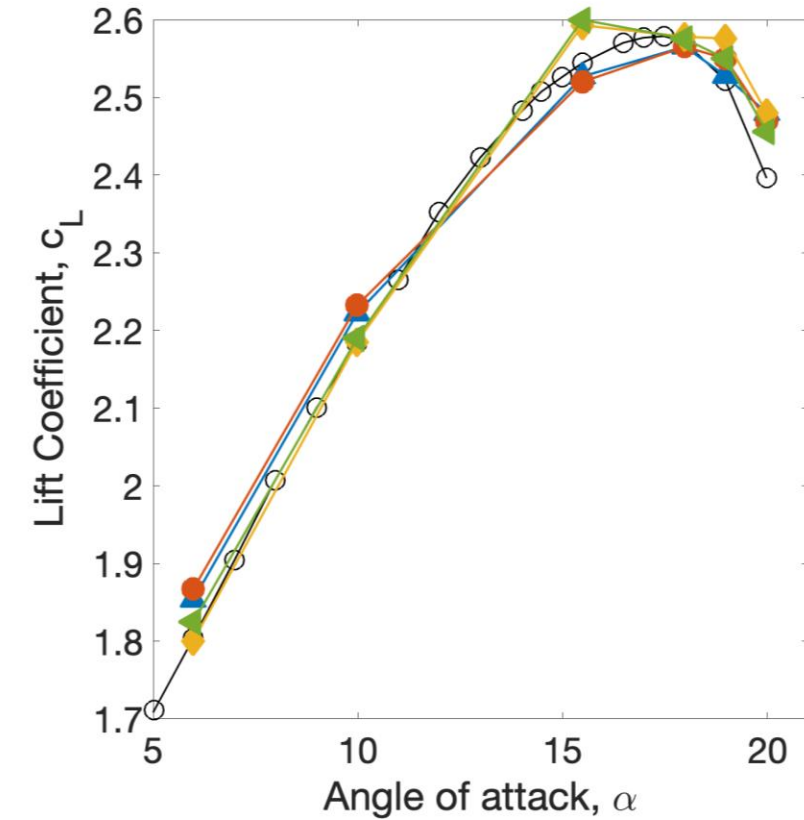
About 2.5 minutes to generate on a workstation

(b) Cartesian Octree Topology

WMLES: Grid Convergence



Cartesian Immersed Boundary (IB)

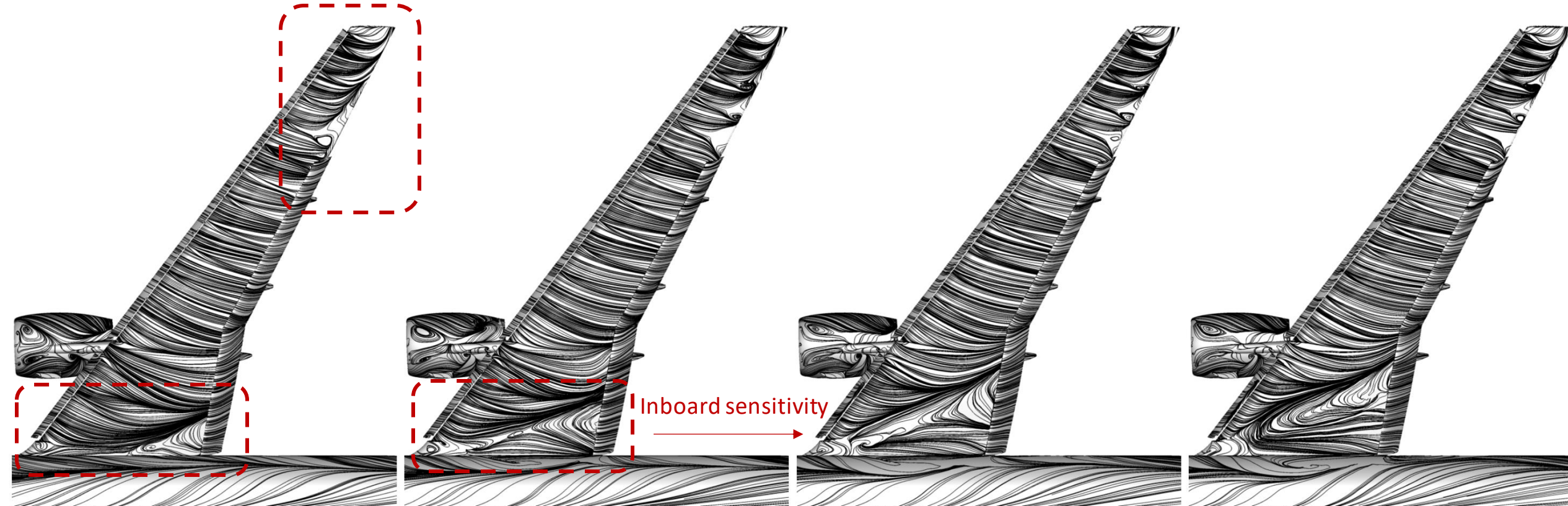


WMLES: Effect of Grid Resolution at CLmax



$$\alpha = 19.98^\circ$$

Time-averaged surface streamlines



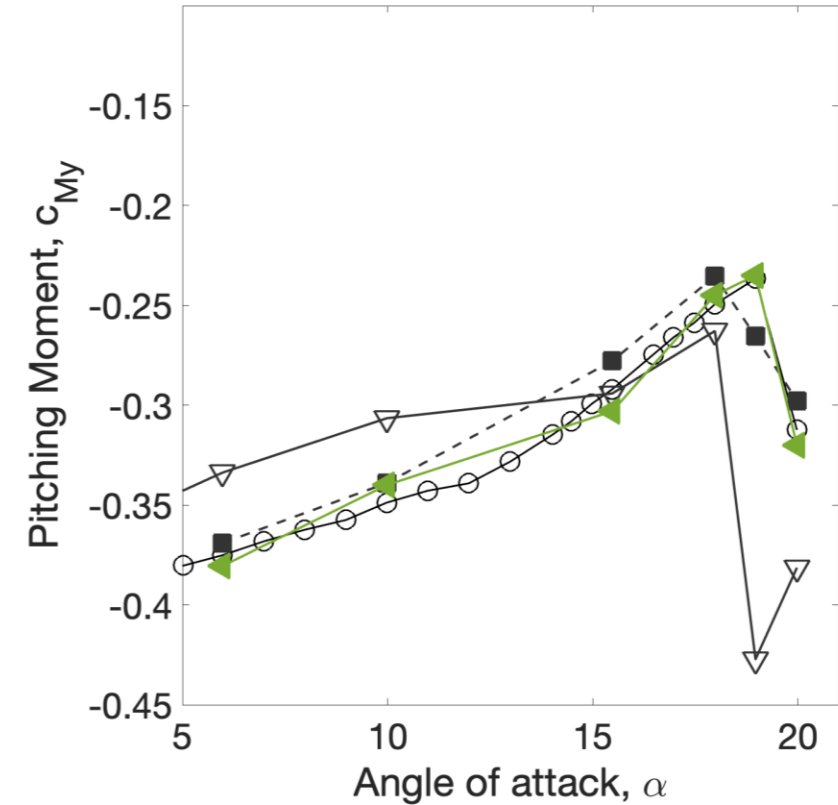
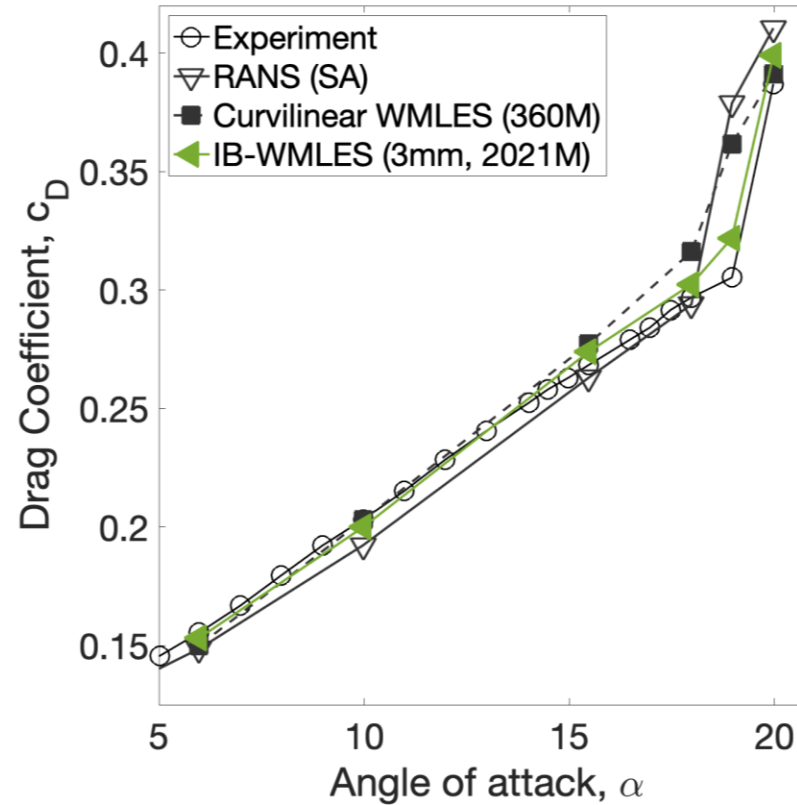
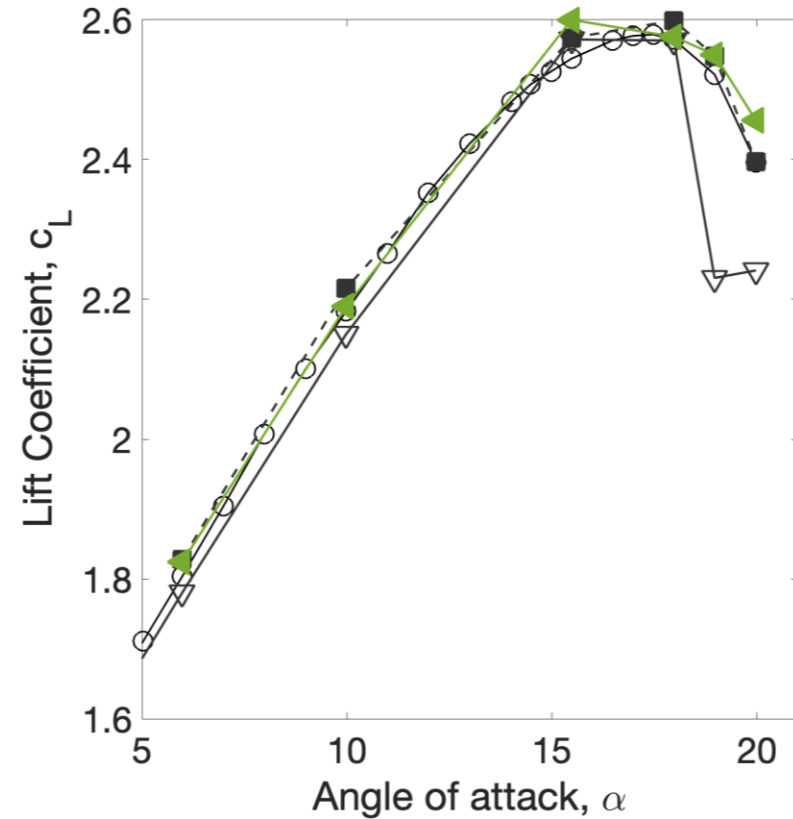
(a) 12mm Grid (100M)

(b) 6mm Grid (450M)

(c) 4mm Grid (1100M)

(d) 3mm Grid (2021M)

WMLES: In-Tunnel Simulations



Refer to paper for information on:

1. Initialization procedure (tunnel back-pressure)
2. Tunnel floor BL comparisons with rake data

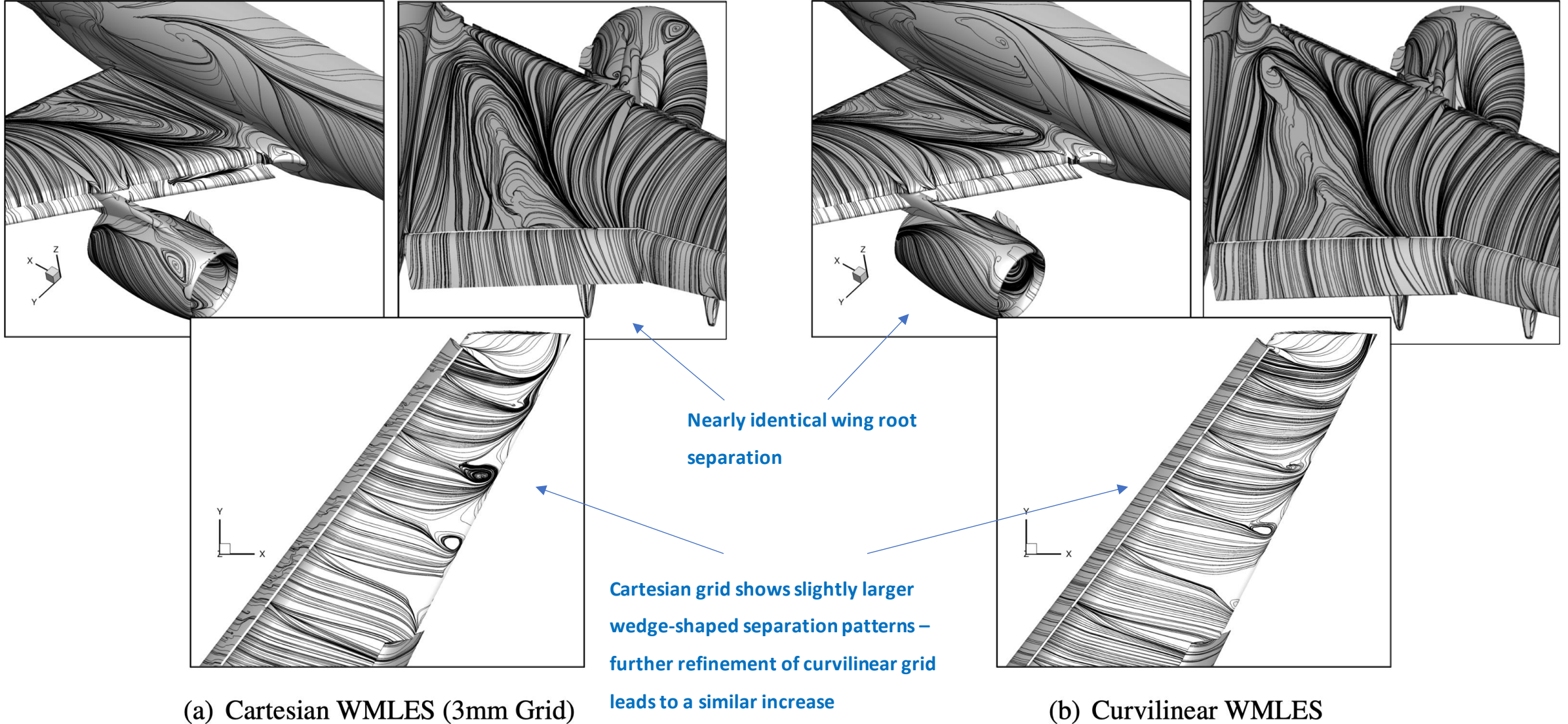
After interpolation to primary/final grid:

1. Transience washout: 10-20 CTU
2. Statistical averaging: 10-30 CTU ($\alpha < 18^\circ$) and 80 CTU ($\alpha > 18^\circ$)

WMLES: Post-CLmax Stalled State



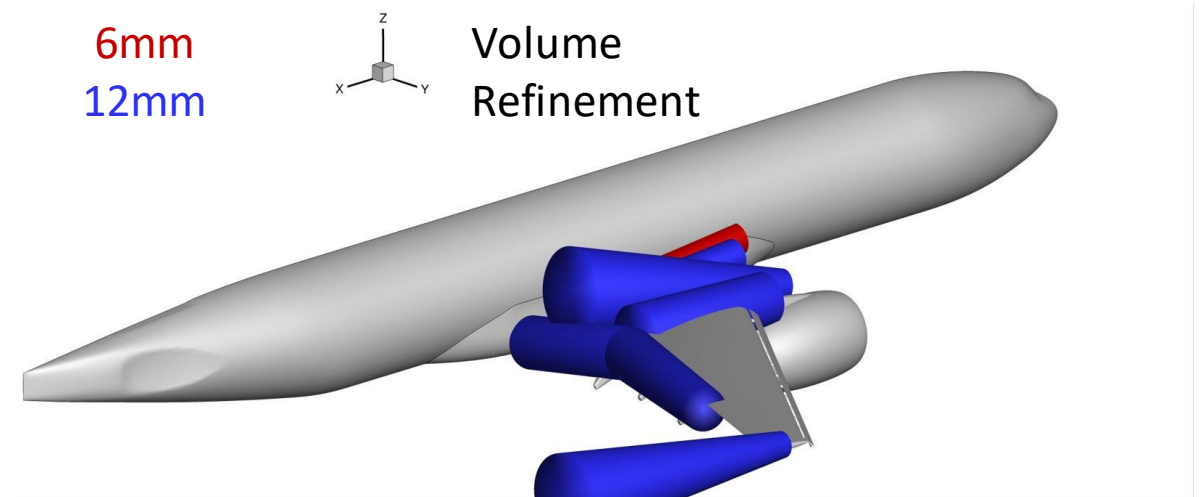
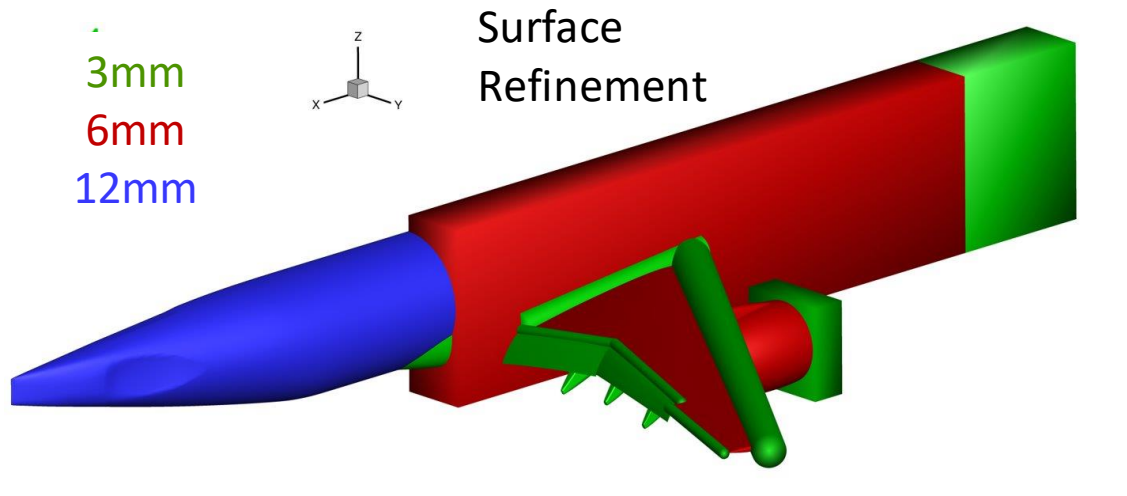
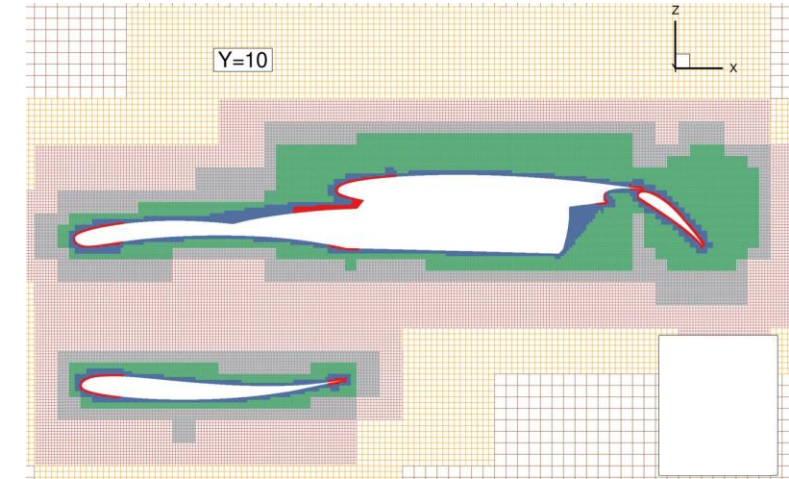
$$\alpha = 19.98^\circ$$



WMLES: Do We Really Need 2 Billion Grid Points?



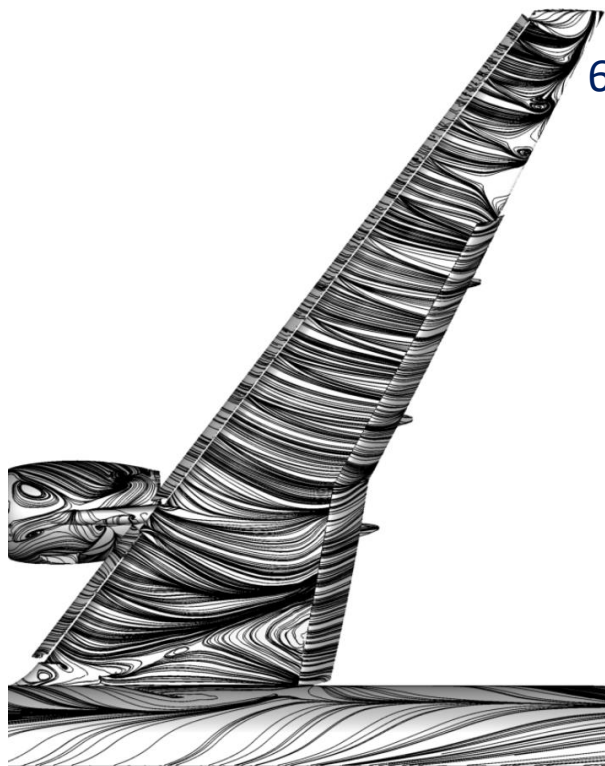
- Engineering “Best-practice” grid can be designed using **targeted refinement** sensitivities shown before



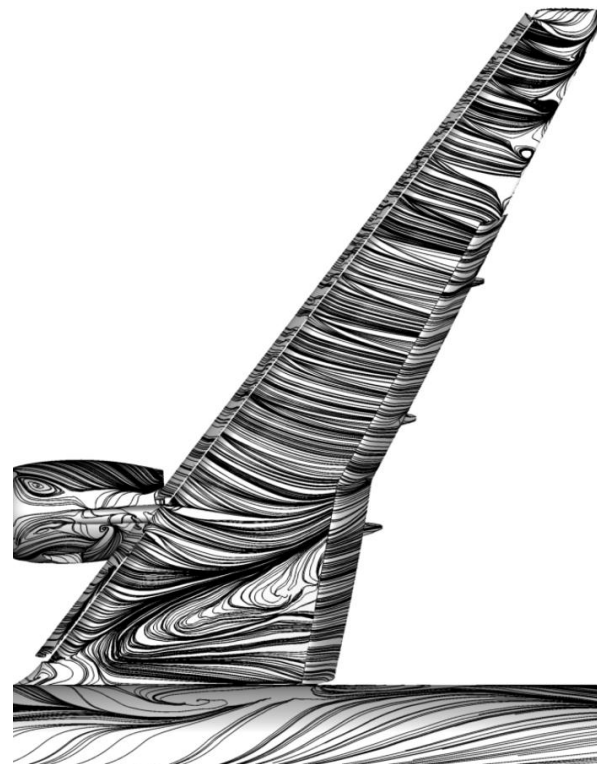
6mm grid (450M) → 3mm + 6mm grid (1000M)*

* Refinement blocks shown above are slightly different from the final refinement strategy that was used

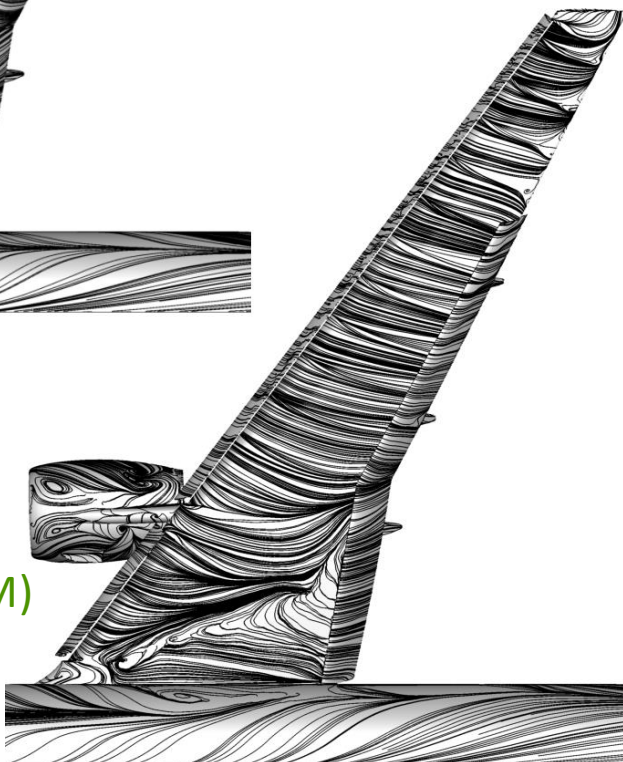
WMLES: “Engineering” Best Practice



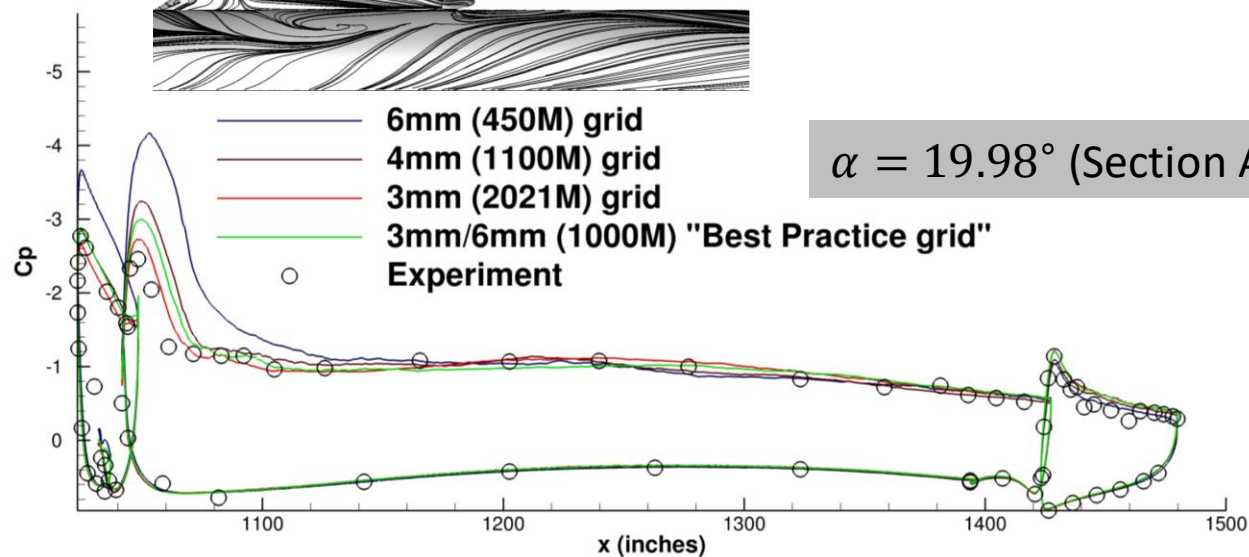
6mm (450M) grid



3mm (2021M) grid



3mm + 6mm (1000M)
“Best Practice grid”



HL-CRM Cost and Timing Comparisons



Attribute	Simulation Methodology				
	RANS (Steady) Grid R-C	RANS (Steady) Grid R-D	WMLES Grid W-B	HRLES Grid H-A	CART-WMLES Grid C-BP
Solve Points	223M	550M	360M	571M	1000M
Timestep size	-	-	$3.5 \times 10^{-6}s$	$2.0 \times 10^{-4}s$	$3.45 \times 10^{-6}s$
Nodes used for benchmark	35 Skylakes (40 cores/node)	100 Broadwells (28 cores/node)	100 AMD Romes (128 cores/node)	200 Skylakes (40 cores/node)	100 Skylakes (40 cores/node)
Core-time per compute point per timestep	-	-	$2.03\mu s$	$139.5\mu s$	$0.75\mu s$
Timesteps per CTU	-	-	29,338	514	29,561
Core-time per CTU	-	-	5970 hours	11360 hours	6100 hours
Simulation time needed for $\alpha = 19.57^\circ$	-	-	50 CTU	50 CTU	50 CTU
Core-time needed for $\alpha = 19.57^\circ$	21,000 hours	44,800 hours	298,500 hours	560,000 hours	308,000 hours
NAS SBUs needed for $\alpha = 19.57^\circ$	835	1,600	9,470	22,120	12,240
Relative Cost over typical RANS	1.0	1.91	11.3	26.4	14.6
Grid Generation (Human Effort)	2-4 months	2-4 months	2-4 months	2-4 months	2-4 hours

Isotropy requires more grid points

Much more efficient algorithm

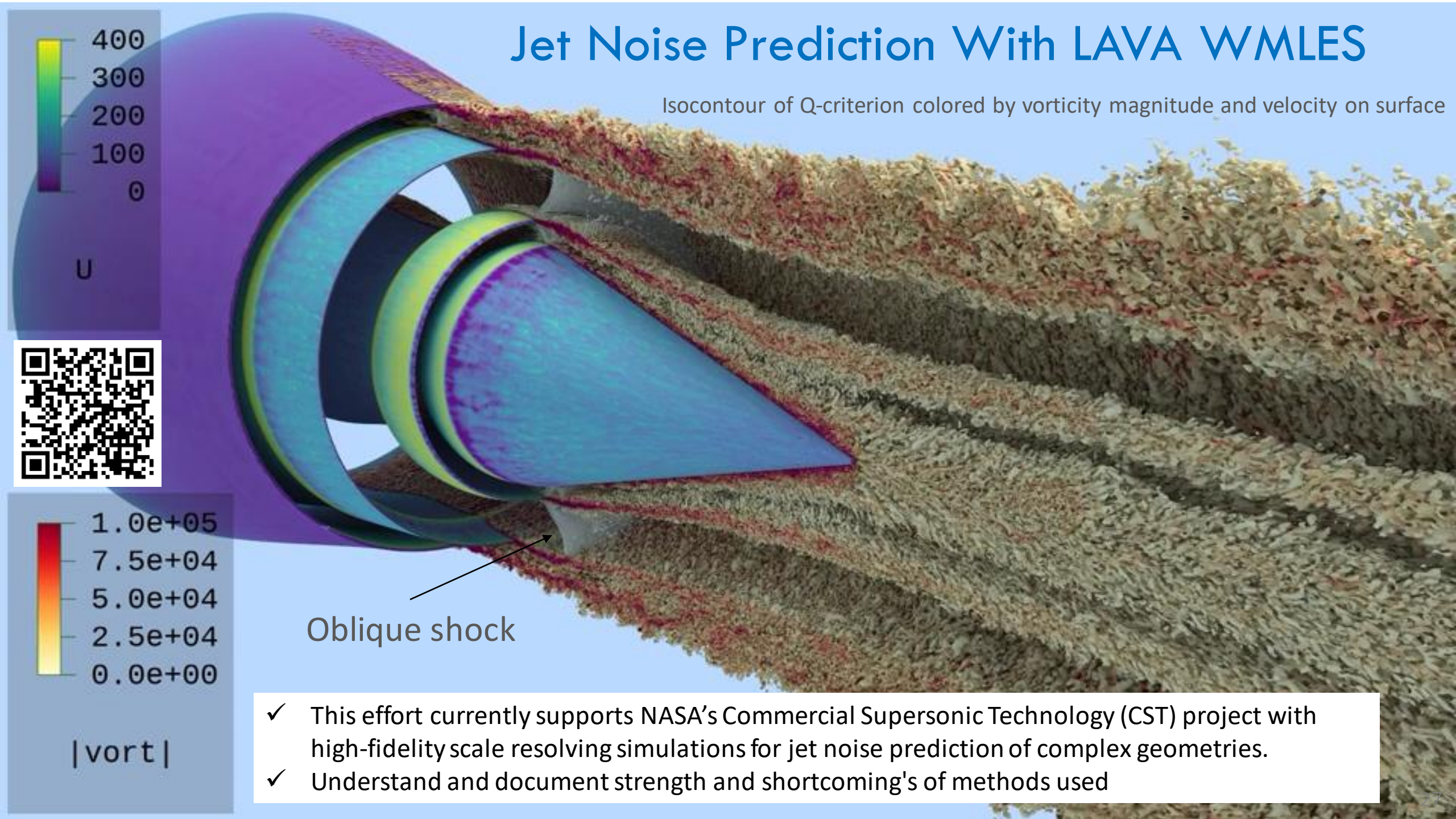
Both Curvilinear and Cartesian WMLES have similar accuracy/cost advantages over RANS

Order of magnitude more expensive than RANS

Negligible human effort for cartesian octree grids (scalable process)

Jet Noise Prediction With LAVA WMLES

Isocontour of Q-criterion colored by vorticity magnitude and velocity on surface



Oblique shock

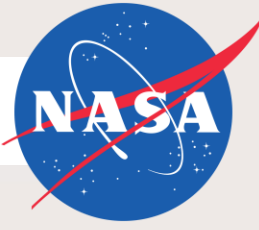
- ✓ This effort currently supports NASA's Commercial Supersonic Technology (CST) project with high-fidelity scale resolving simulations for jet noise prediction of complex geometries.
- ✓ Understand and document strength and shortcoming's of methods used



The Launch, Ascent and Vehicle Aerodynamics (LAVA) framework

Objectives within NASA's CST project for Jet Noise

- Predict jet noise **accurately** and in **short enough turnaround time** using **scale-resolving** simulations methods
- **Understand** and document **uncertainties and shortcomings** of scale-resolving wall-modeled LES for jet noise simulations
- **Future Impact:** complement/replace wind tunnel and flight tests, reduction of associated costs, provides insight into noise reduction technology never-before available. Aide in the creation of FAA guidelines for supersonic vehicles during landing and takeoff



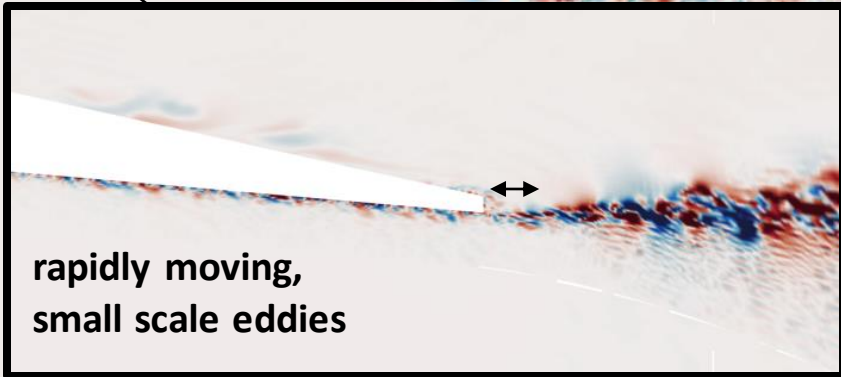
Why are Scale-Resolving Jet Noise Simulations Challenging/Expensive?

Domain size of jet simulation region: $140D_{\text{exit}}$

Length scale: $0.02D$

Sweeping Timescale: $0.05 D/U$

nozzle



Length scale: $20.0D$

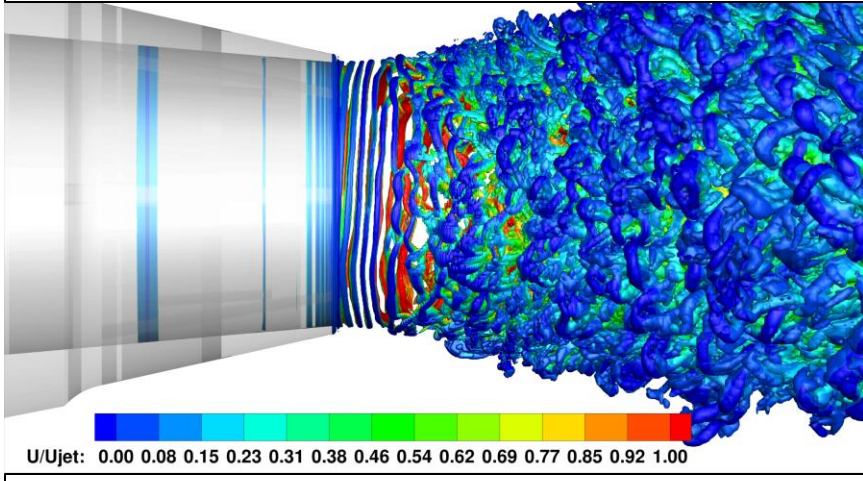
Sweeping Timescale: $522 D/U$
very slow, large scale eddies



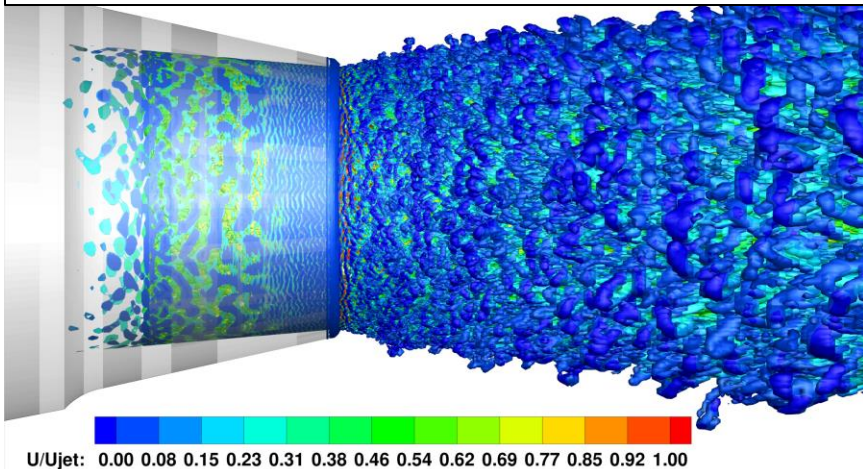
VVel: -25 -20 -17.5 -15 -10 -5 0 5 10 15 17.5 20 25

2017: Round Jet Validation - Hybrid RANS/LES

DDES-256M

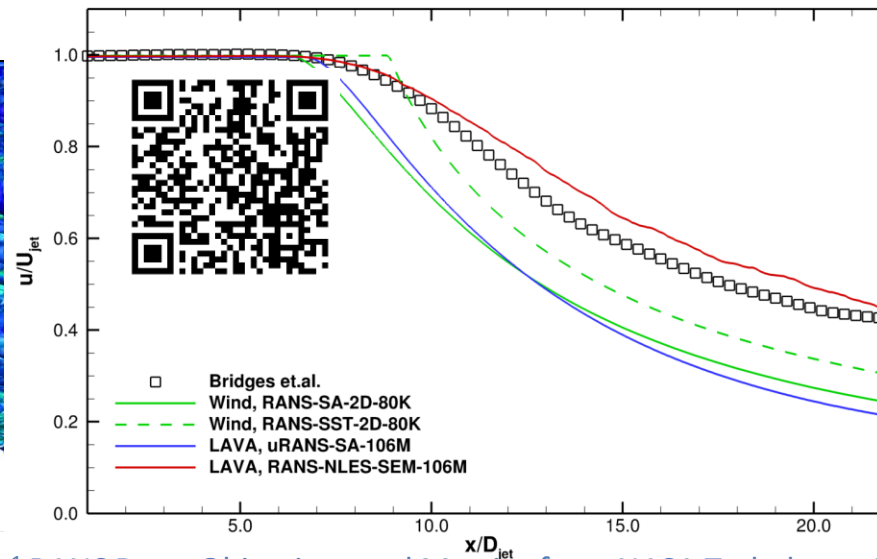


ZDES-106M



NASA Revolutionary Computational Aerosciences (RCA) challenge for jet noise:

- **Goal:** Improve Simulation accuracy by 40%
- Prediction of length of potential core ($U/U_j = 0.98$)
- Improvement of centerline TKE Prediction
- See AIAA-2017-3213 for more information



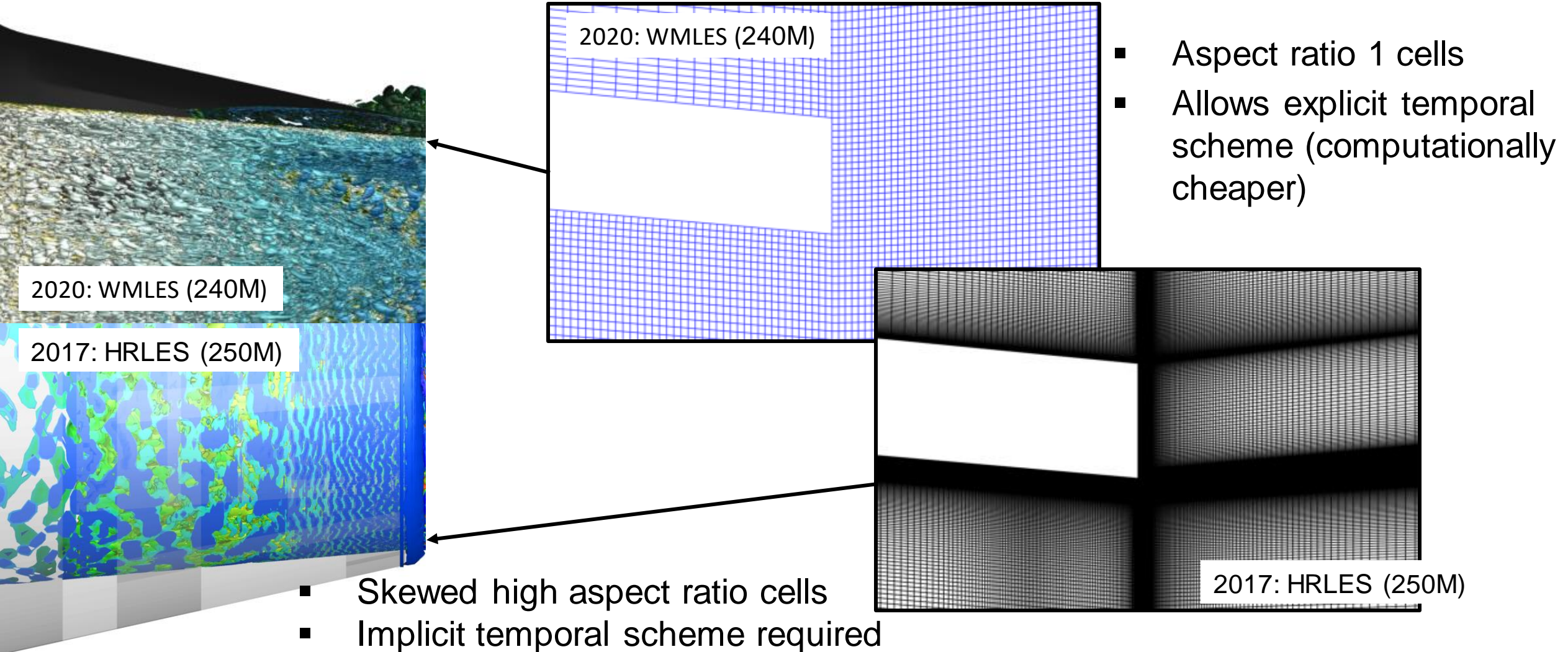
89.6% improvement

solver	Error [%]
Bridges & Wernet Exp.	-
State-of-the-Art SA-RANS ¹	-12.3
LAVA Hybrid RANS/LES	1.2

¹ RANS Data, Objectives and Metrics from NASA Turbulence Modeling Resource (TMR) website

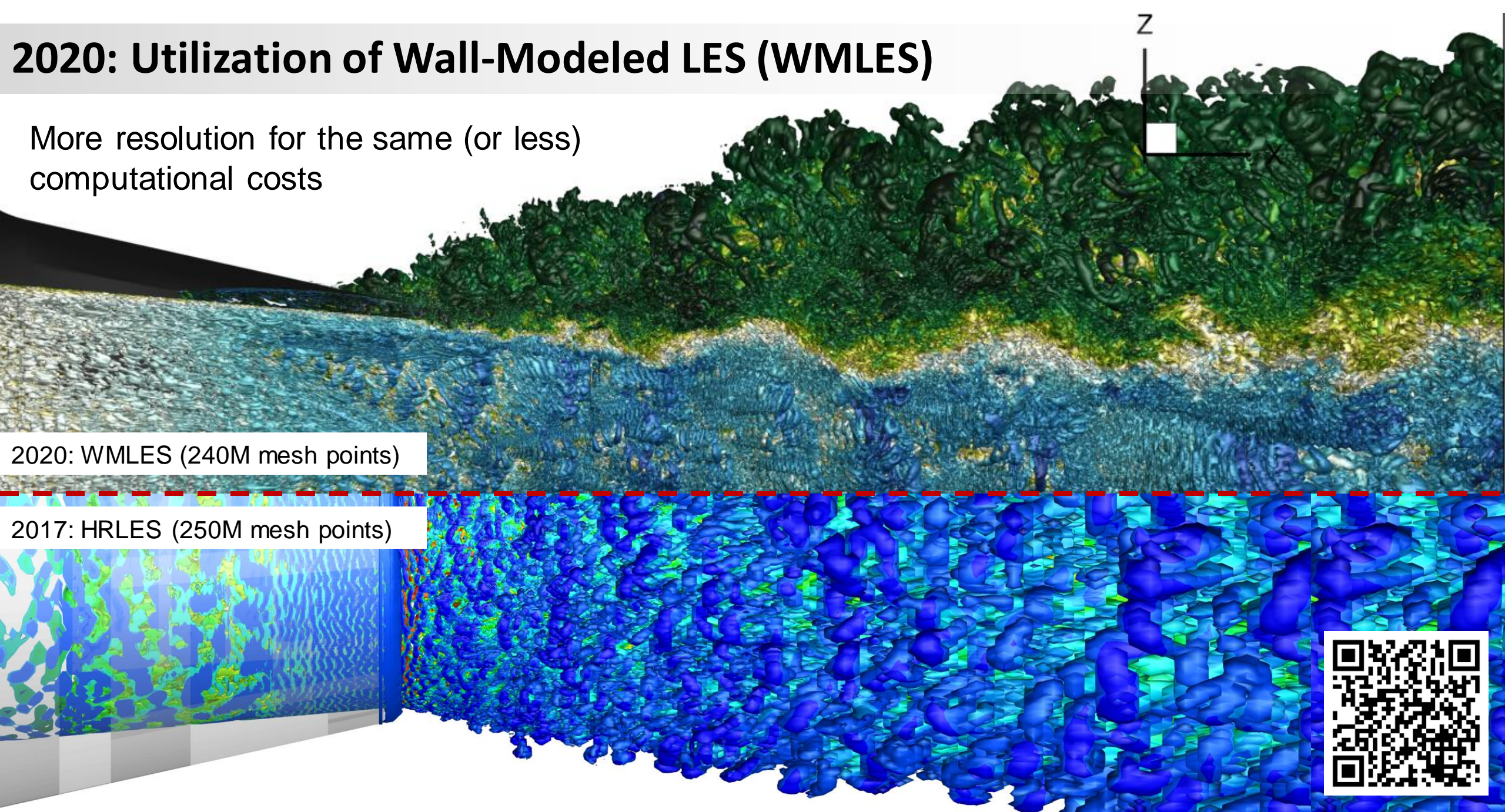
2020: Utilization of Wall-Modeled LES (WMLES)

- Points from resolving near-wall gradients distributed throughout the domain
- Improved aspect ratio (AR) allows "better" numerical treatment (less dissipation)



2020: Utilization of Wall-Modeled LES (WMLES)

More resolution for the same (or less)
computational costs



2020: WMLES (240M mesh points)

2017: HRLES (250M mesh points)

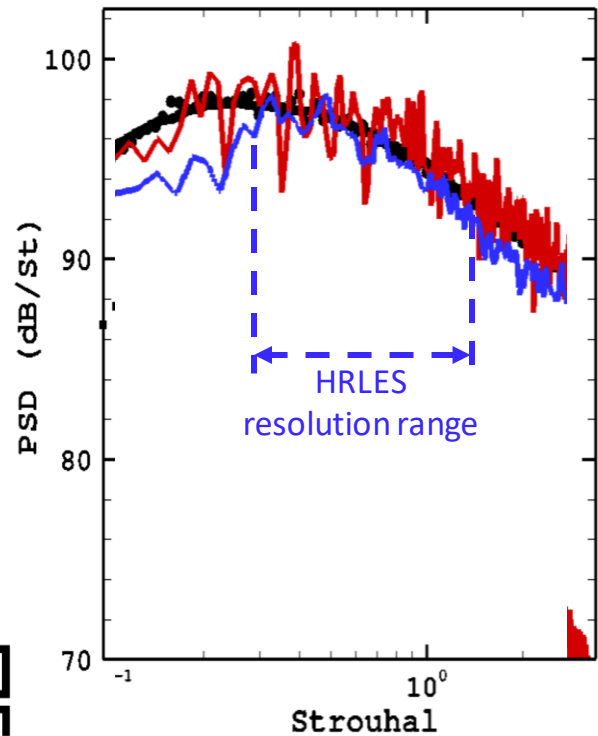


Timings and Improvements – Implications for Science

For the identical number of mesh point we can now:

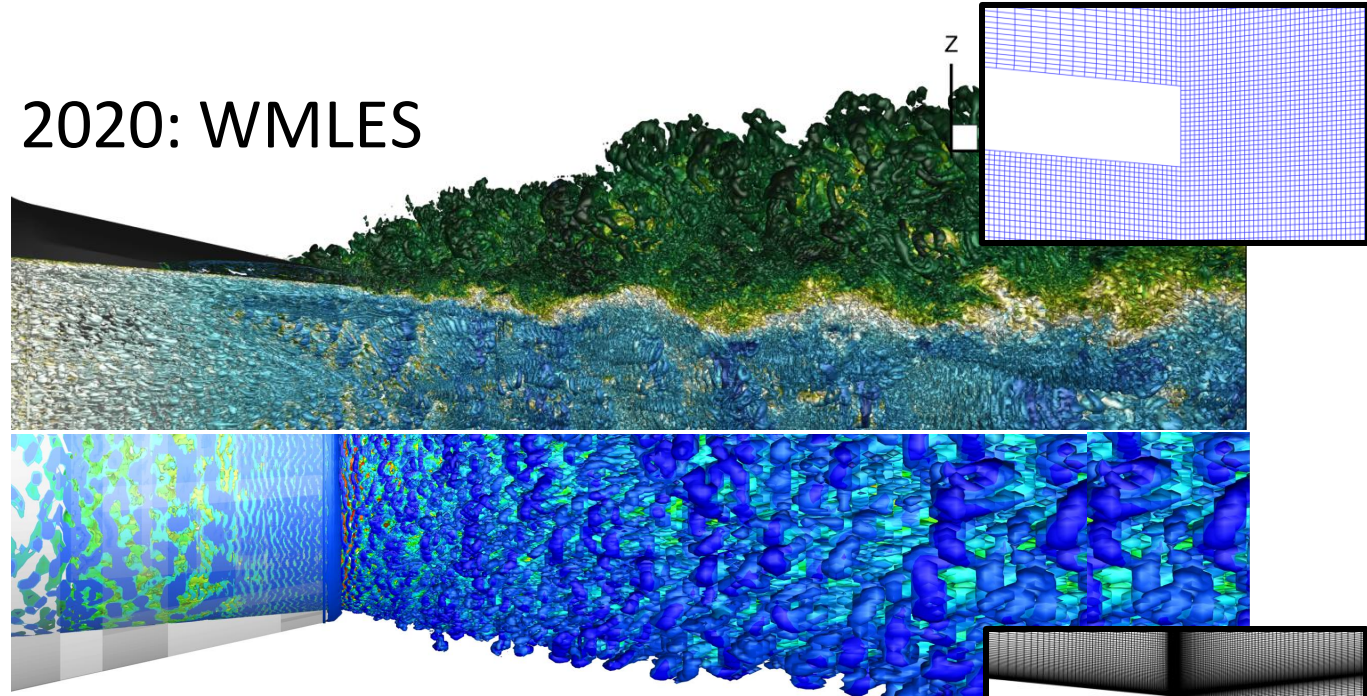
- Redistribute points over a wider area

WMLES 2021 | Hybrid RANS/LES 2019

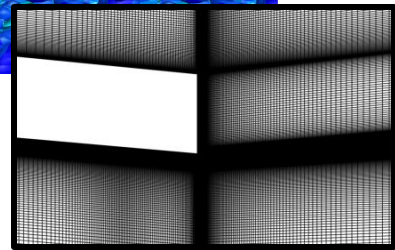


Noise at observer location 100D
away from the nozzle exit

2020: WMLES



2017: HRLES

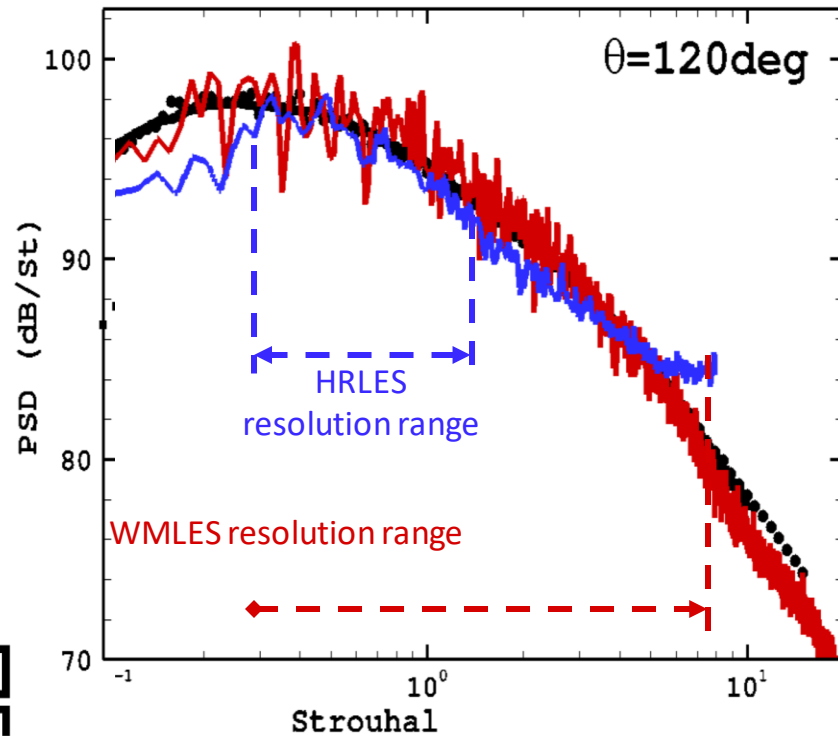


Timings and Improvements – Implications for Science

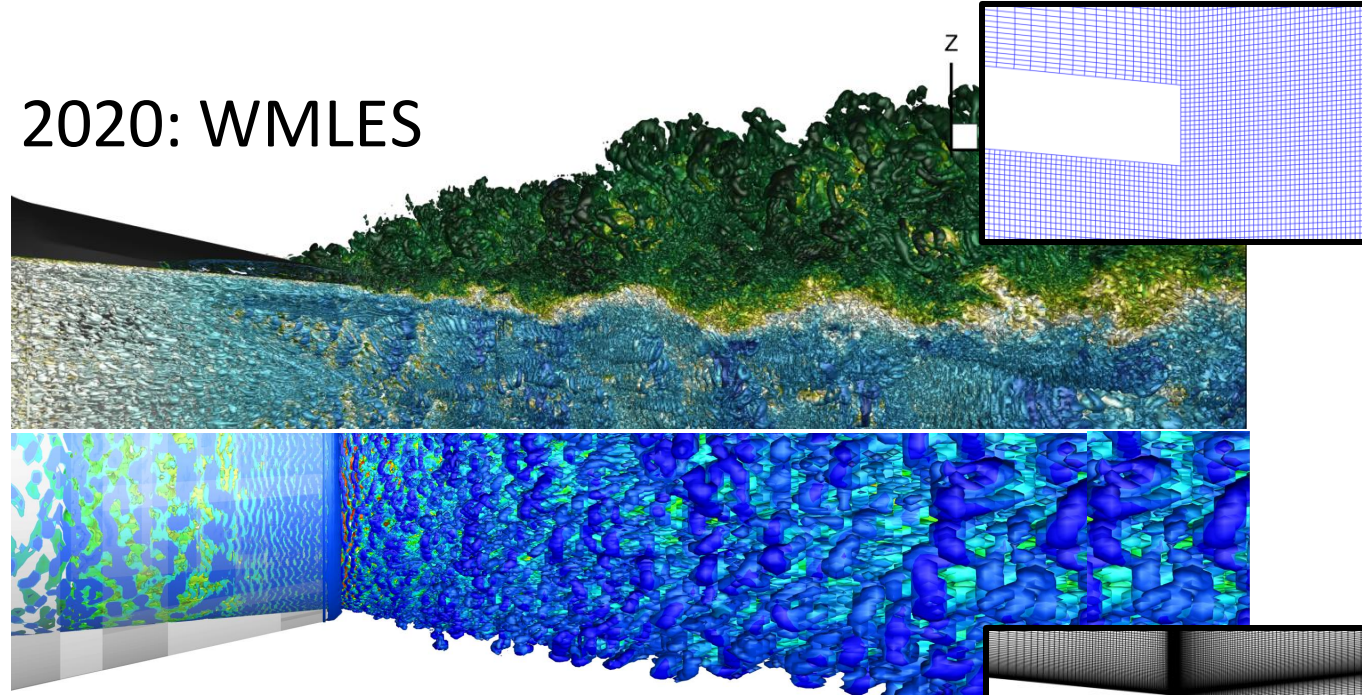
For the identical number of mesh point we can now:

- Redistribute points over a wider area → increased high frequency resolution

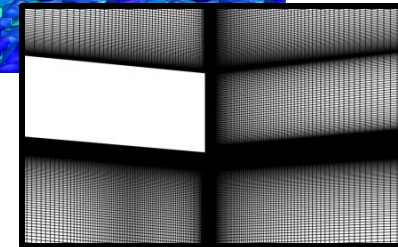
WMLES 2021 | Hybrid RANS/LES 2019



2020: WMLES



2017: HRLES



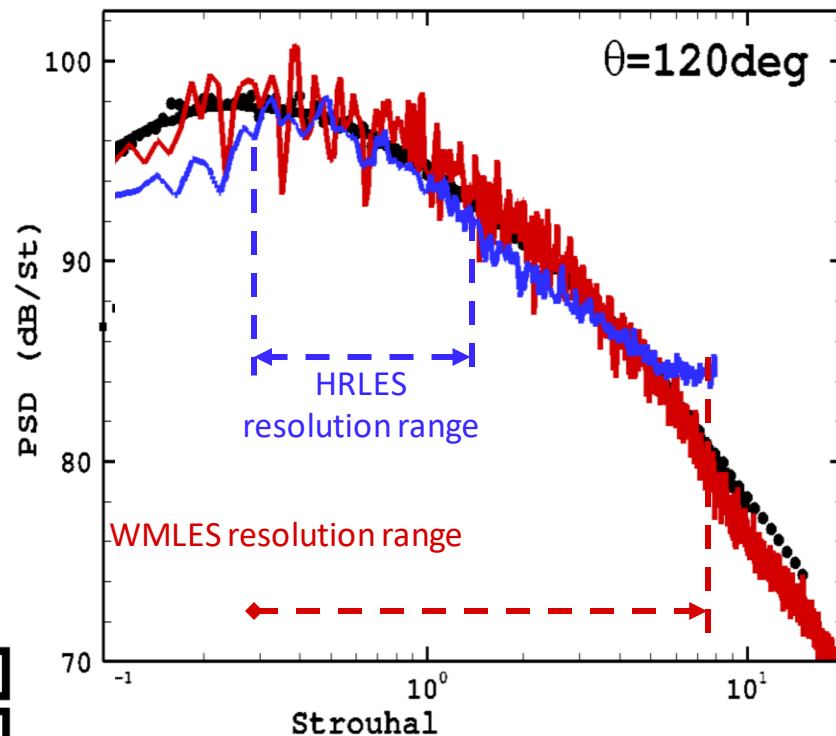
Upper frequency range extended for almost a decade of data



Timings and Improvements – Implications for Science

For identical simulation time cost (CPUh) we can now:

- Increase simulation time interval



Path towards a robust, reliable and fast WMLES solver for jet noise database generation

November 2019

Hybrid RANS/LES

6.5 days [100 Broadwell]

Current

WMLES + Optimized Code & Best Practices & Scaling

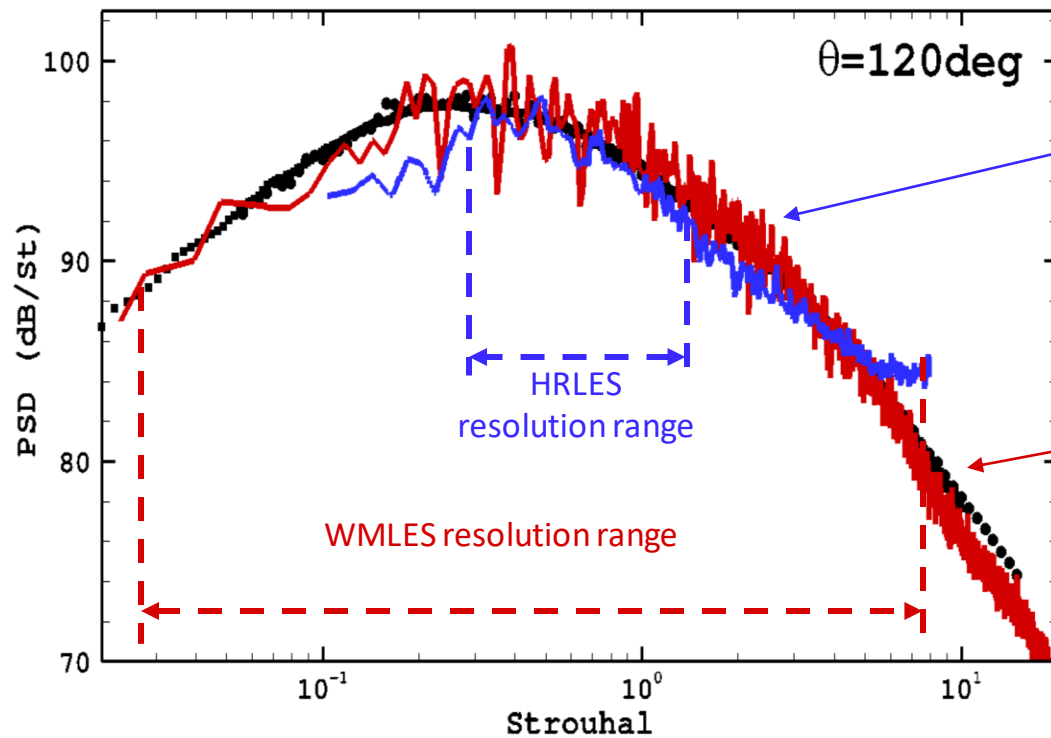
150 minutes [100 Rome]



Timings and Improvements – Implications for Science

For identical simulation time cost (CPUh) we can now:

- Increase simulation time interval → extend lower frequency resolution range



HRLES Simulation for SP7

6.5 days
60 Skylake Nodes
2,400 cores

300 CTU

WMLES Simulation for SP7

0.6 days
100 AMD Rome Nodes
12,800 cores

2000 CTU

6.6x more simulation time, still
factor of 10x faster solution
turnaround

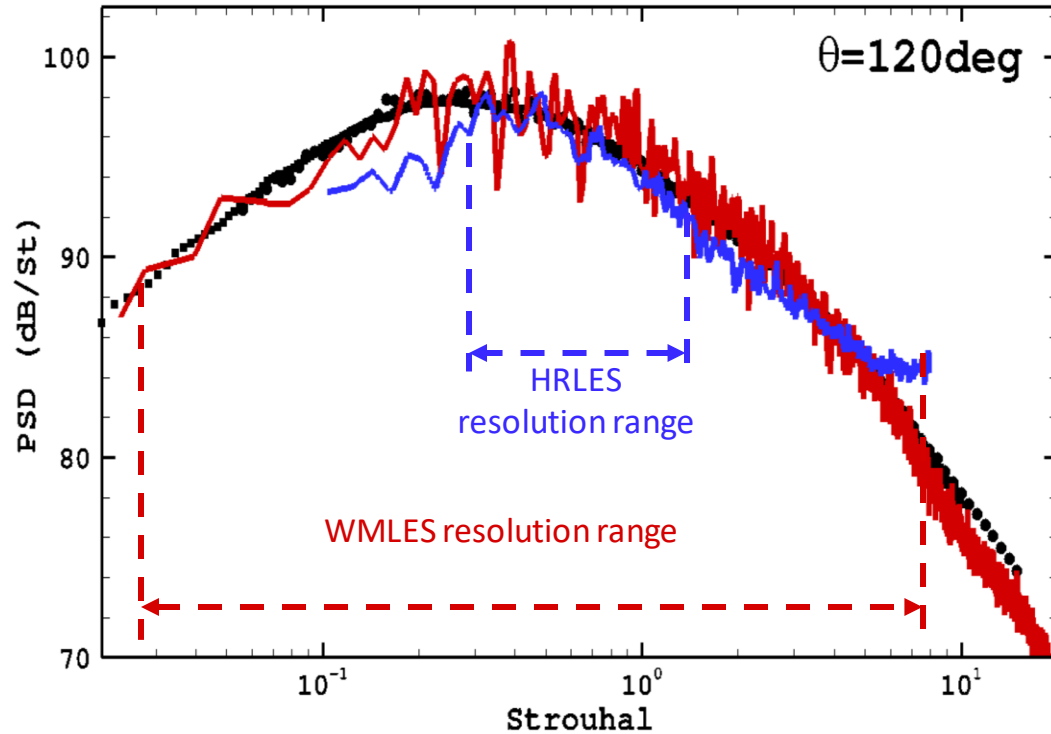


Upper and lower frequency range extended for almost a decade each way

Timings and Improvements – Implications for Science

For the identical simulation time cost (CPUh) we can now:

- Increase number of simulations in the same amount of time



static

Set Point SP	Ma [-]	M _j [-]	M _∞ [-]	NPR [-]	NTR [-]	Exp. Data	
						PIV	MIC
3	0.50	0.51	0.0	1.197	0.96	✓	✓
7	0.90	0.98	0.0	1.852	0.84	✓	✓
23	0.50	0.38	0.0	1.102	1.76	✓	✓
27	0.90	0.68	0.0	1.368	1.76	✓	✓
29	1.33	1.00	0.0	1.898	1.76	✓	✓
38	1.33	0.88	0.0	1.664	2.27	✗	✓
46	0.90	0.56	0.0	1.219	2.70	✓	✓
49	1.48	0.90	0.0	1.697	2.70	✓	✓
101240	1.14	0.85	0.0	1.608	1.78	✗	✓
In-flight							
100084	1.32	1.09	0.3	2.110	1.48	✗	✓
100024	1.01	0.85	0.3	1.616	1.40	✗	✓
100274	1.20	0.99	0.3	1.875	1.47	✗	✓
101244	1.13	0.85	0.3	1.603	1.78	✗	✓

Code improvements enable new frontiers in WMLES for jet noise





Timings and Code Improvements

Time savings due to algorithm, code improvements and development

Date	Method	Mesh size [10 ⁶]	$\Delta t/c_\infty$	CPU	Time/CTU [CPUh]	Time to solution 150 / 300 convective units	Speedup (November baseline)
November 2019	Hybrid RANS/LES (ZDES III)	225	0.007	60 Skylake (2400 cores)	995	3.2 day / 6.5 day	--
March 2020	Wall-stress WMLES	254	0.0005	60 Skylake (2400 cores)	430	26.8 hr / 2.3 day	2.8x
November 2020	Wall-stress WMLES	110	0.001	60 Skylake (2400 core)	69	4.3 hr / 8.6 hr	18x
March 2022	Wall-stress WMLES	250	0.0007	100 Rome (12800 core)	106	75min / 150 min	62X

CTU: Convective Flow Through Unit

* Timings include high frequency (sampling rate 200kHz) i/o output for solution

** Substantially better temporal resolution and spatial resolution (azimuth, stream) achieved compared to baseline November 2019

*** Improvements possible due to improved scalability of code (scales well up to 10-20k pnts/core)

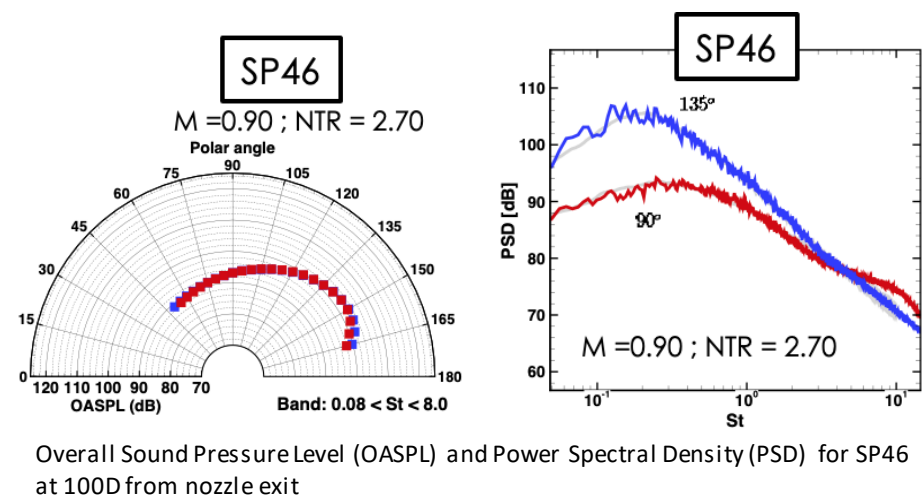


Database Generation using WMLES for Jet Noise using LAVA

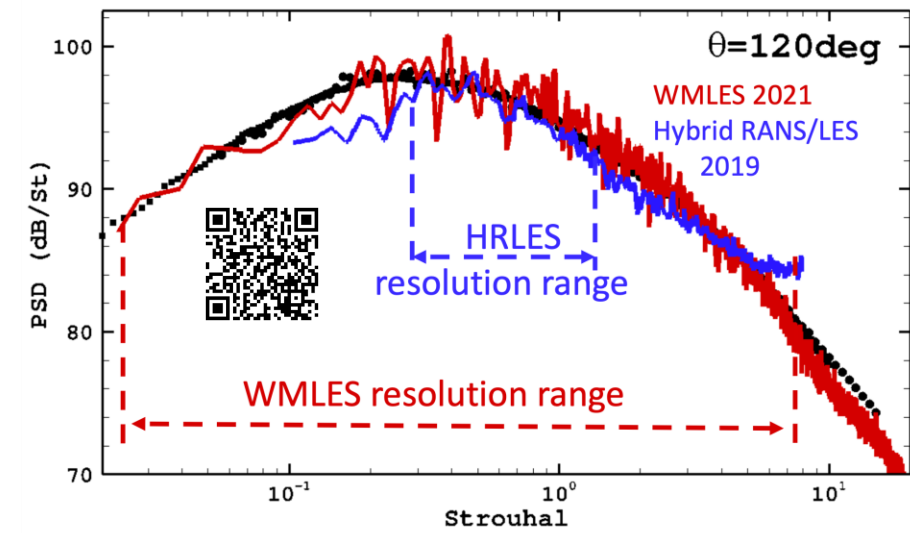
- WMLES successfully applied to the prediction of jet noise within NASA CST**
 - Significant improvements in turnaround times (63x) compared to hybrid RANS/LES have been demonstrated
 - Improvements have enabled simulations previously not feasible
- A first of it's kind database was generated utilizing WMLES within LAVA for NASA CST's Prediction Uncertainty Reduction (PUR) technical challenge.**
 - A total of 20 different flow configurations have been simulated using high-fidelity scale-resolving LES
 - Each simulation takes around 24hr and generates 100 TB of data
 - Excellent agreement with experiments within 1dB (comparable to experimental rig-to-rig uncertainty)

Set Point SP	Ma [-]	M _j [-]	M _∞ [-]	NPR [-]	NTR [-]	Exp. Data PIV MIC
3	0.50	0.51	0.0	1.197	0.96	✓ ✓
7	0.90	0.98	0.0	1.852	0.84	✓ ✓
23	0.50	0.38	0.0	1.102	1.76	✓ ✓
27	0.90	0.68	0.0	1.368	1.76	✓ ✓
29	1.33	1.00	0.0	1.898	1.76	✓ ✓
38	1.33	0.88	0.0	1.664	2.27	✗ ✓
46	0.90	0.56	0.0	1.219	2.70	✓ ✓
49	1.48	0.90	0.0	1.697	2.70	✓ ✓
101240	1.14	0.85	0.0	1.608	1.78	✗ ✓
100084	1.32	1.09	0.3	2.110	1.48	✗ ✓
100024	1.01	0.85	0.3	1.616	1.40	✗ ✓
100274	1.20	0.99	0.3	1.875	1.47	✗ ✓
101244	1.13	0.85	0.3	1.603	1.78	✗ ✓

PUR DatabaseSet Points



Improved resolution range for far-field noise at 100D from nozzle exit



Stich et. al. AIAA2022-3002 & AIAA2022-0684

Path towards a robust, reliable and fast WMLES solver for jet noise database generation

November 2019

Hybrid RANS/LES

6.5 days [100 Broadwell]

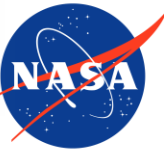
63 x speedup

Today

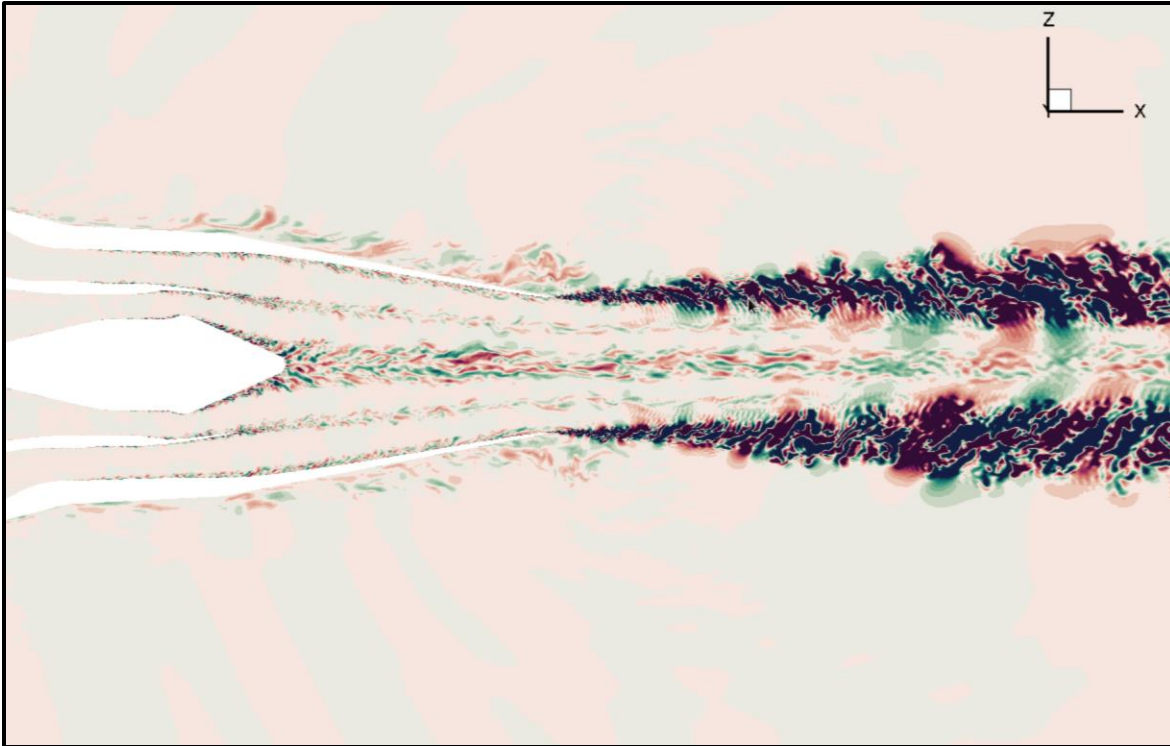
WMLES + Optimized Code & Best Practices & Scaling

150 minutes [100 Rome]

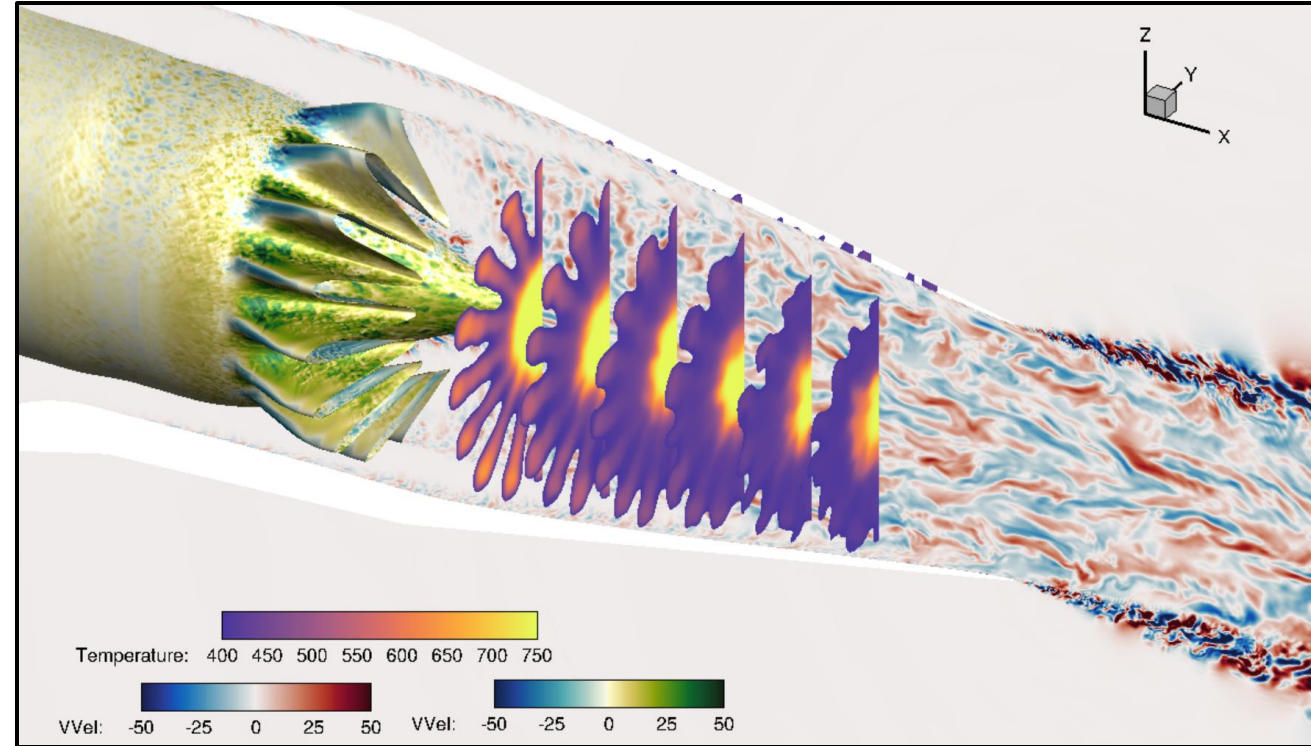
Towards More Realistic Nozzle Configurations



Plug 20 axisymmetric mixer



Plug 20 lobed mixer

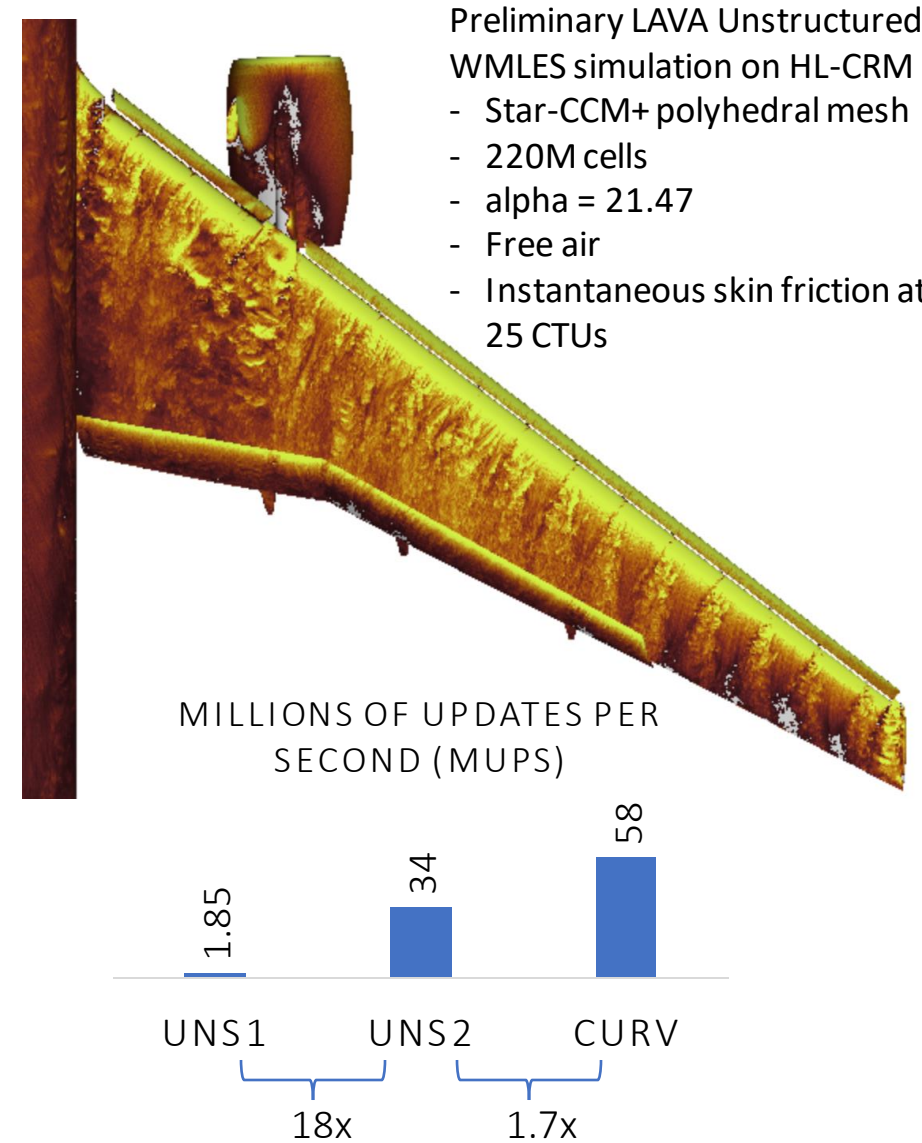


- Demonstrated good agreement for canonical configurations
- Moving towards more realistic jet configurations including internal mixers (axisymmetric & lobed)

LAVA Unstructured Solver for WMLES



- LAVA Unstructured solver has been refactored to achieve high computational efficiency and scalability on CPUs
 - Achieved ~18X speed-up over the legacy LAVA unstructured
- Low dissipation fluxes and models needed for WMLES has been implemented and validated using fundamental test problems
- GPU porting of LAVA Unstructured is in progress
- Preliminary simulations of the HL-CRM were conducted using Star-CCM+ generated arbitrary polyhedral meshes
 - Demonstrated excellent robustness and scalability
- However, we are reaching the limit of commercial meshing tools for large, scale-resolving meshes (e.g., HL-CRM)
 - Not scalable to billions of elements
 - Non-ideal unstructured cell quality results in excessive dissipation
 - No ability to strictly control minimum cell size in order to use an explicit time-stepping scheme with a reasonable step size



LAVA Voronoi Mesher for WMLES

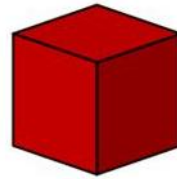


- Voronoi meshing allows for highly automated and scalable body-fitted mesh creation
 - Inherent Voronoi properties results in a high-quality mesh, ideally suited to LES applications
- Development effort has been ongoing to implement LAVA Voronoi mesher with properties:
 - **Completely automated (user inputs: surface geometry, simple text file for sizing regions)**
 - **Coarse/fine interface refinement ratios and blending smoothness can be easily controlled**
 - **Body-aligned layers**
 - Near-body cells are clipped using the geometry with automatic de-featuring of sub-cell details
 - i.e. no manual work needed to simplify geometries
 - High performance, scalable implementation with MPI/OpenMP parallelism (in progress)

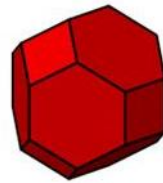
"Growing" of Voronoi cells from seeds



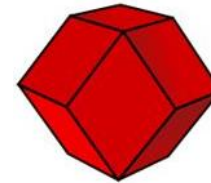
Various cell types can be generated by seeding accordingly



Cube
(Cartesian)

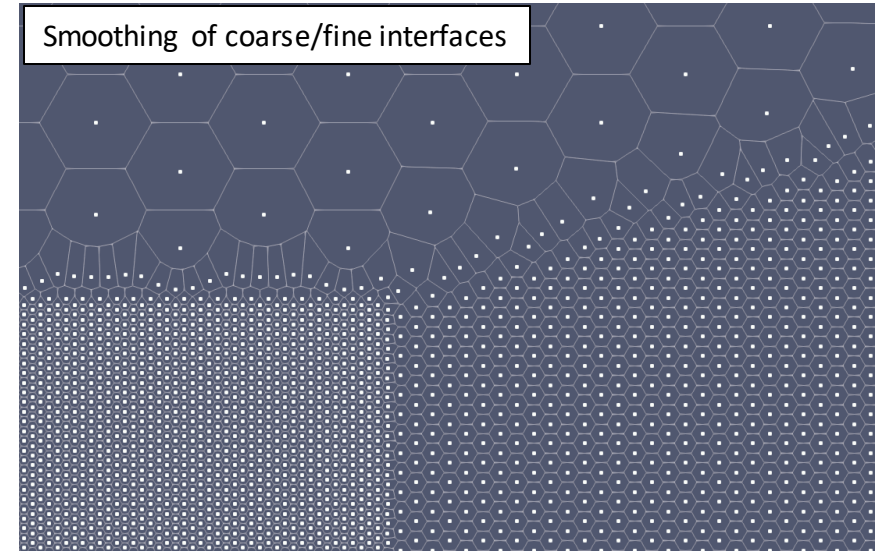


Truncated octahedral
(body-centered cubic)

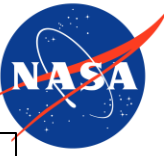


Rhombic dodecahedral
(face-centered cubic)

Smoothing of coarse/fine interfaces

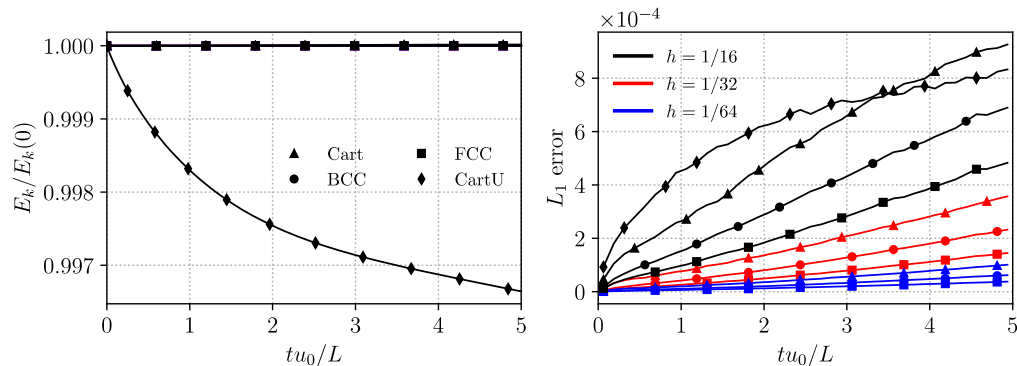
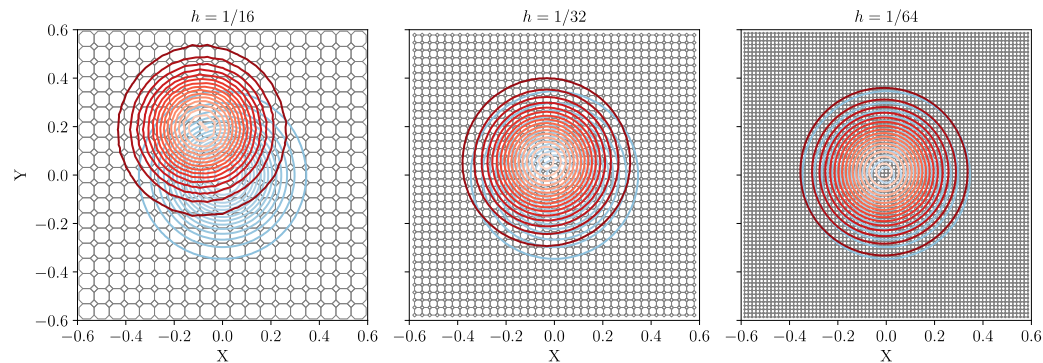
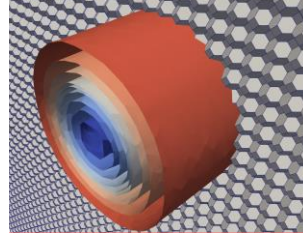


LAVA Voronoi LES Capability Verification



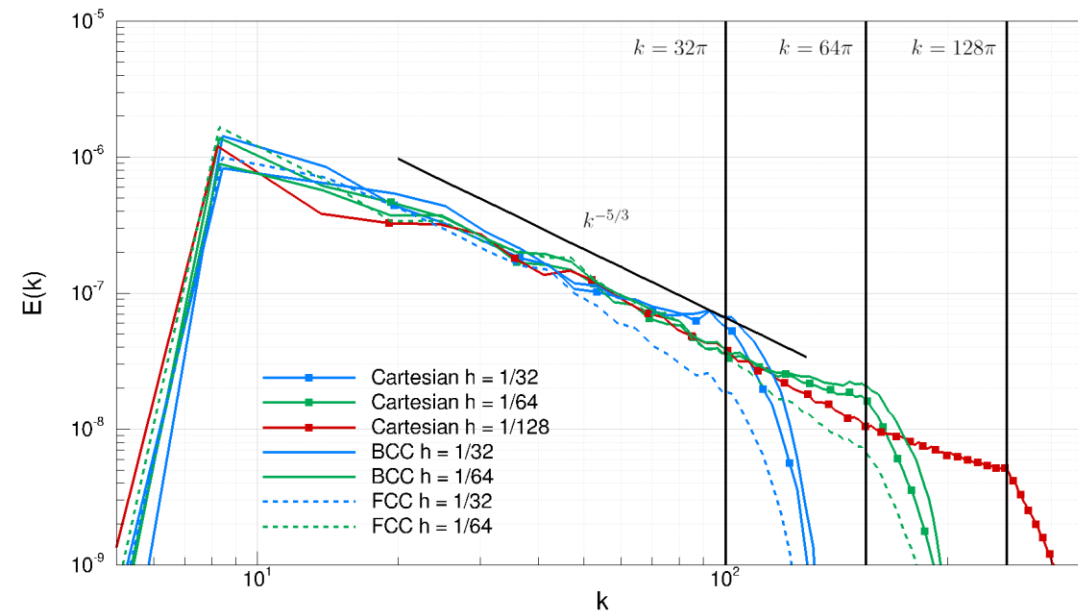
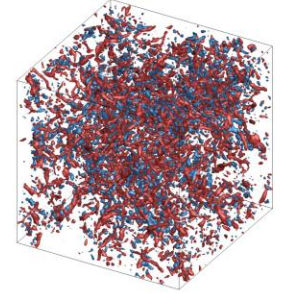
Isentropic Vortex Propagation

- Central convective flux is non-dissipative, with 2nd order solution error convergence for all grid types
- Dispersion errors manifest as drift
- For the same grid spacing, Cartesian has the largest error, FCC has the least (at higher cost)



Homogeneous Isotropic Turbulence (HIT)

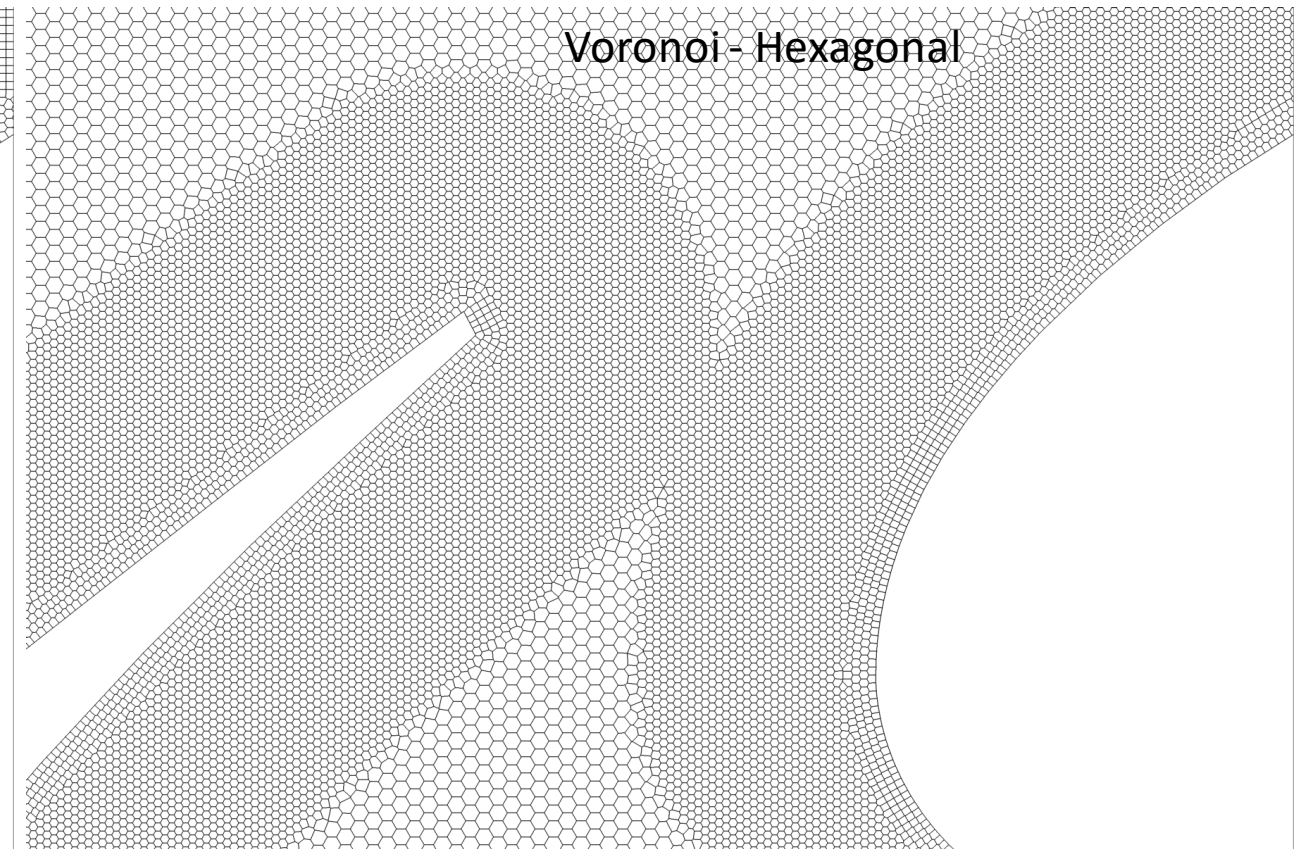
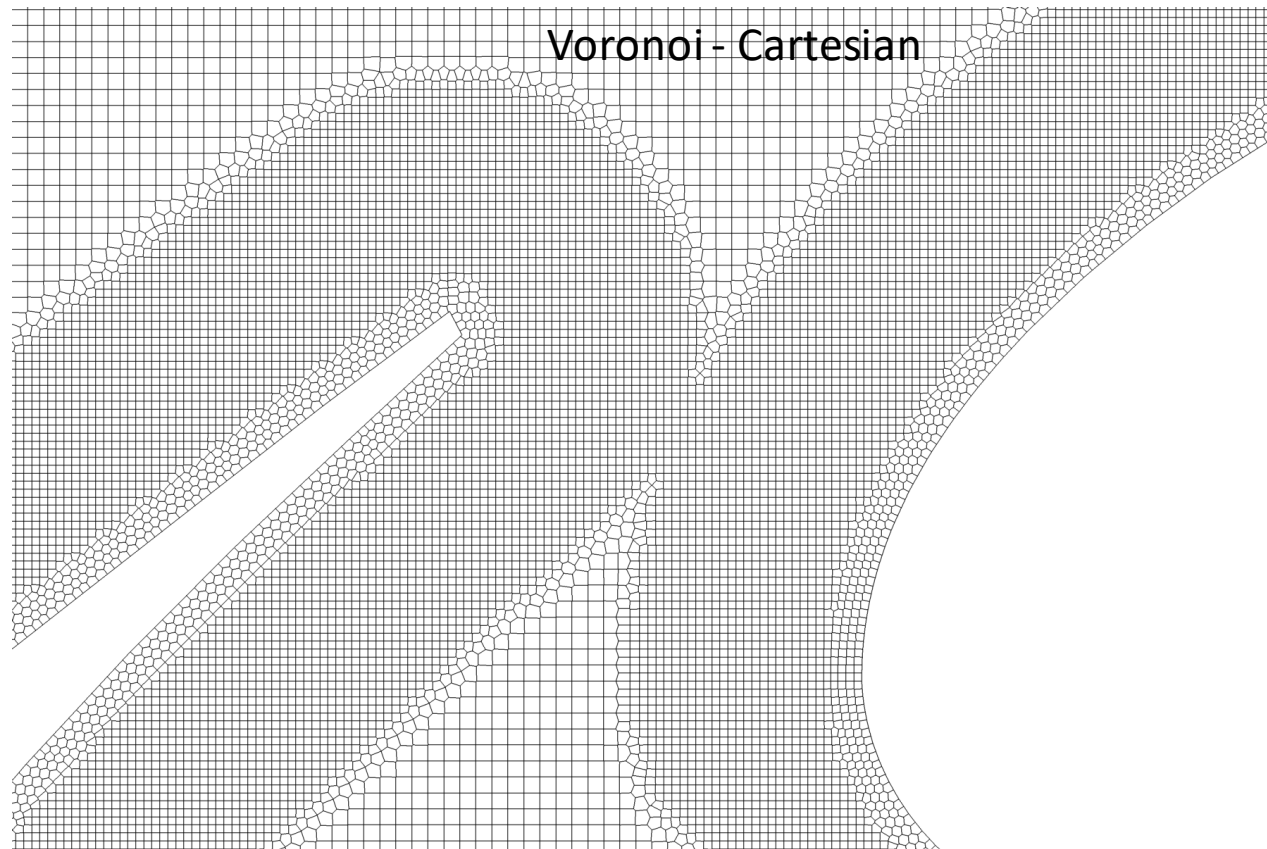
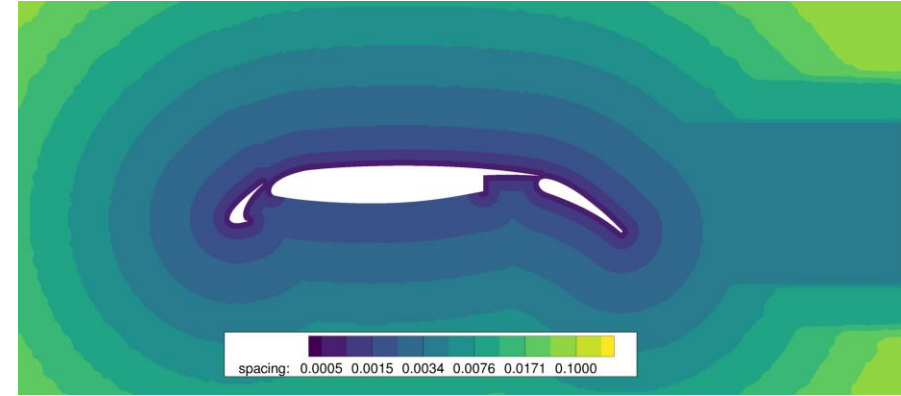
- HIT with a momentum forcing source was studied
- Energy decay rate at the inertial rate is correctly predicted
- Onset of rapid dissipation at the sub-grid scale is captured at correct Nyquist wave numbers for all cell types



LAVA Voronoi WMLES – 30P30N Mesh



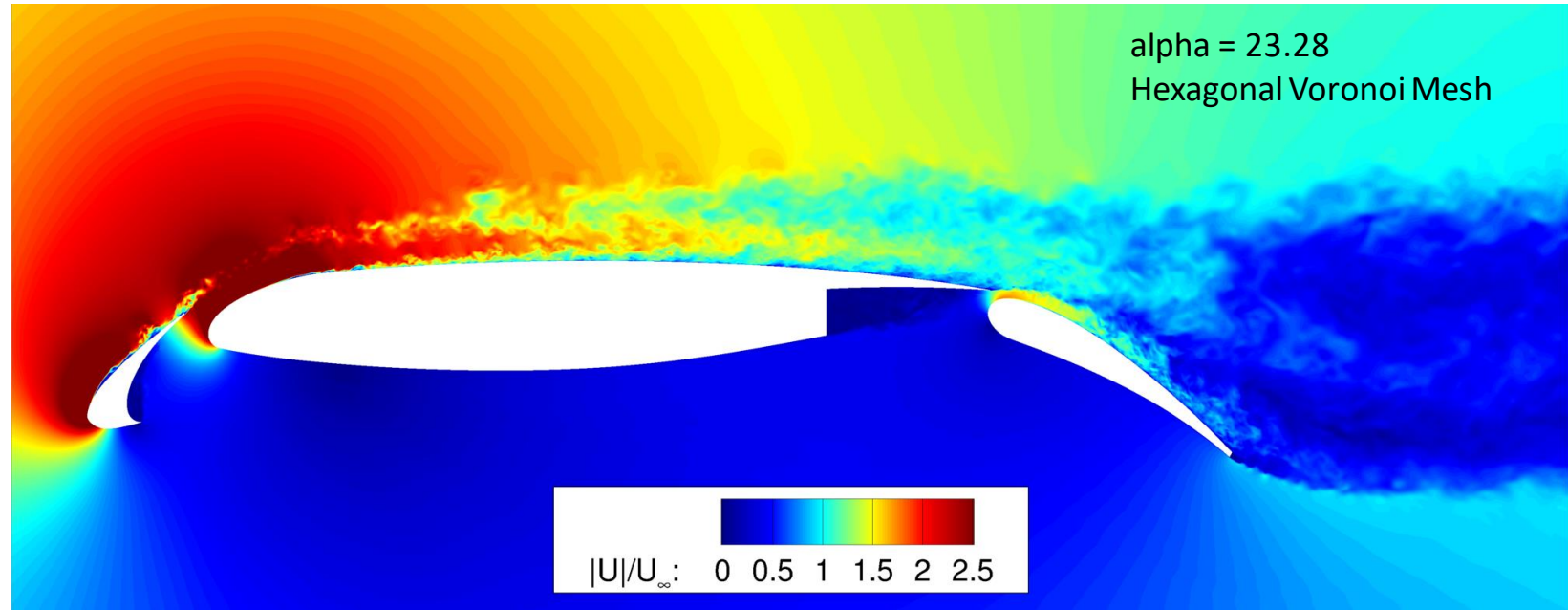
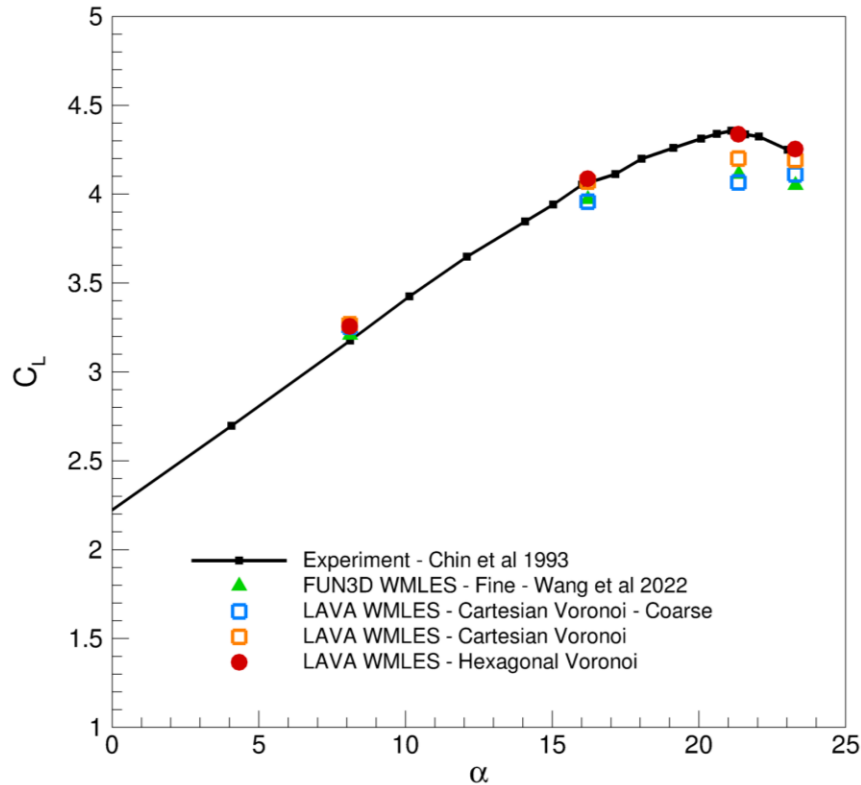
- Multi-element airfoil meshed using telescoping wall-distance based refinement zones
 - 1.5x coarsening factor for each consecutive band
 - Added wake refinement box
- 4 body-aligned wall layers
- Created both Cartesian and hexagonal type meshes



LAVA Voronoi WMLES – 30P30N Results



- $Ma = 0.2$, $Re = 9e6$,
- 3D, 10% chord simulated span-wise with periodic boundary conditions
- Wall-modeled LES with subgrid scale model and central blended convective flux formulation

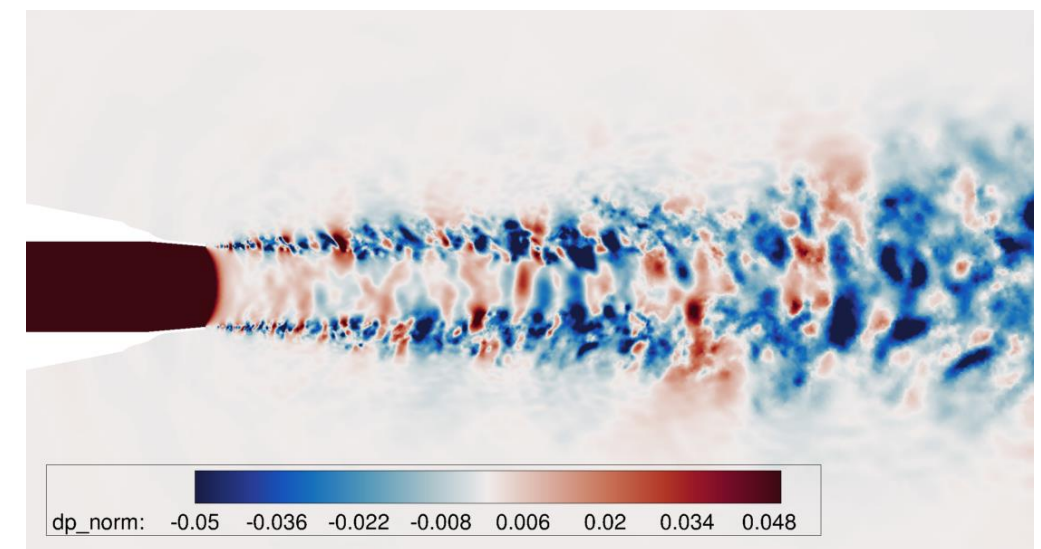
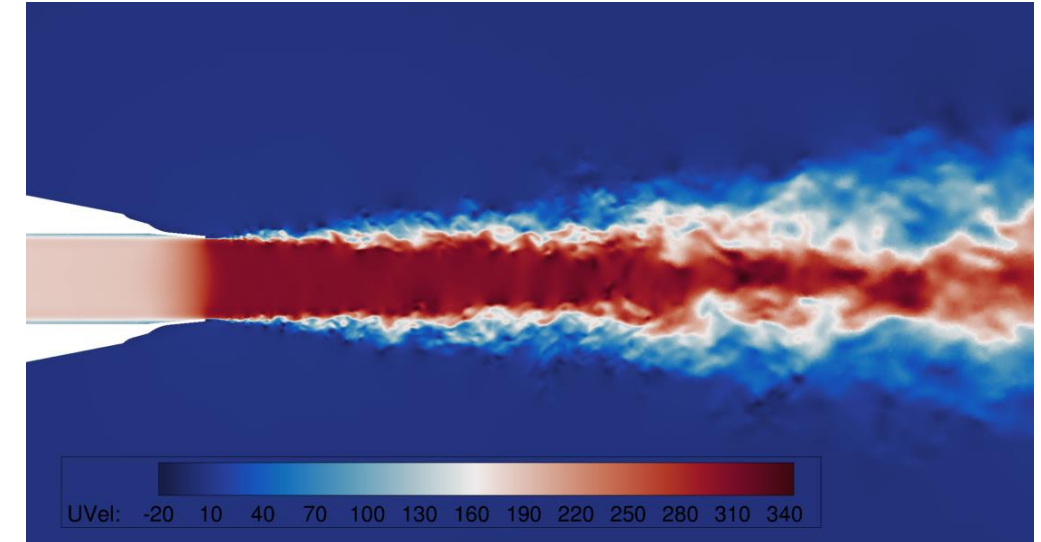
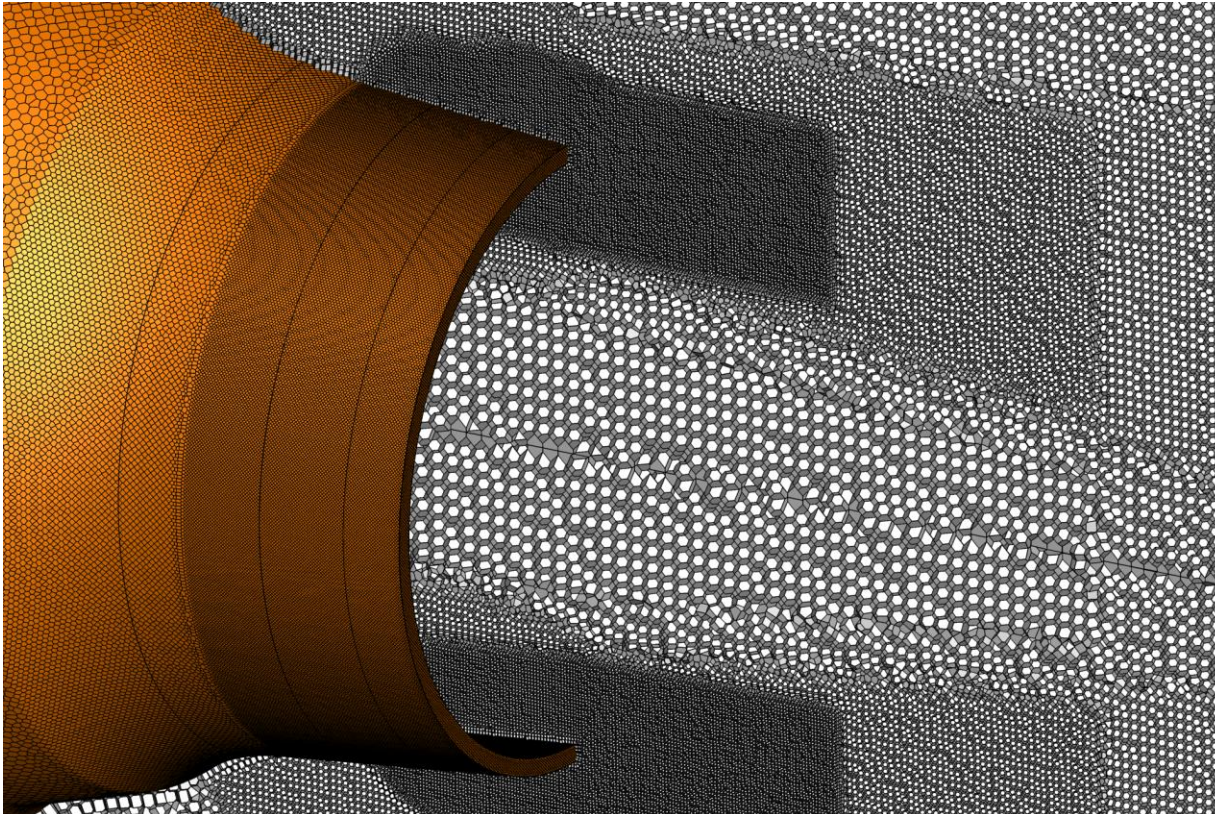


Mesh	# Cells (millions)	Span extent (% chord)
LAVA Voronoi - Hexagonal	51	10
LAVA Voronoi - Cartesian	42	10
FUN3D – Mixed Element - Fine	10	4

LAVA Voronoi WMLES – Jet Acoustics



- We are in the process of applying the Voronoi unstructured approach to jet acoustics
- High level of control over coarse/fine interface smoothness is desirable to address spurious acoustic reflections
- Preliminary results are very encouraging





LAVA Unstructured GPU Porting – Outlook

- Out of the top 15 fastest systems worldwide, all but 2 rely on GPU accelerators
- GPU porting of LAVA Unstructured WMLES is in progress
 - Uses **CUDA**; retains much of the same structure as the CPU code which is well optimized
- Benchmarks on hexahedral meshes were performed during 2022 NAS/NVIDIA GPU Hackathon
 - MUPS: Millions of UPdates (timesteps) per Second → Higher is better
 - **MUPS/W: MUPS per unit Power** → Higher is better
 - A100 had **8.5X higher** performance (in MUPS)
 - A100 had **6.4X higher** power efficiency than Skylake (in MUPS/W)

Architecture	Type	MUPS	Power, TDP (W)	MUPS/W	Theoretical Peak Flops (TF)	Theoretical Peak Bandwidth (GB/s)
2x Intel Skylake 6148 (AVX512)	CPU	35	300	0.12	3.1	230
1x Nvidia A100 (CUDA)	GPU	298	400	0.75	9.7	1600
GPU/CPU Ratio		8.5	1.3	6.4	3.1	7.0

Summary and Outlook



- **HRLES and WMLES within LAVA have demonstrated improved predictive capability relative to RANS for problems dominated by highly complex flow physics**
 - *High-lift aerodynamics*: Comprehensive study for the HL-CRM using variable levels of fidelity demonstrated the capability for scale-resolving methods to accurately predict highly separated flows
 - *Aeroacoustics*: Scale-resolving simulations demonstrate ability to accurately capture tonal and broadband noise for various applications
- **Potential for Voronoi mesh technology to offer level of accuracy consistent with LAVA Curvilinear HRLES and WMLES but with reduced manual overhead related to grid generation**
- **Research presented here is ongoing and future work will seek to refine scale-resolving simulation best-practices and apply these methods to additional configurations**
- **Investigation to evaluate benefits and speed-up of GPU accelerated architectures for scale-resolving simulations is underway**



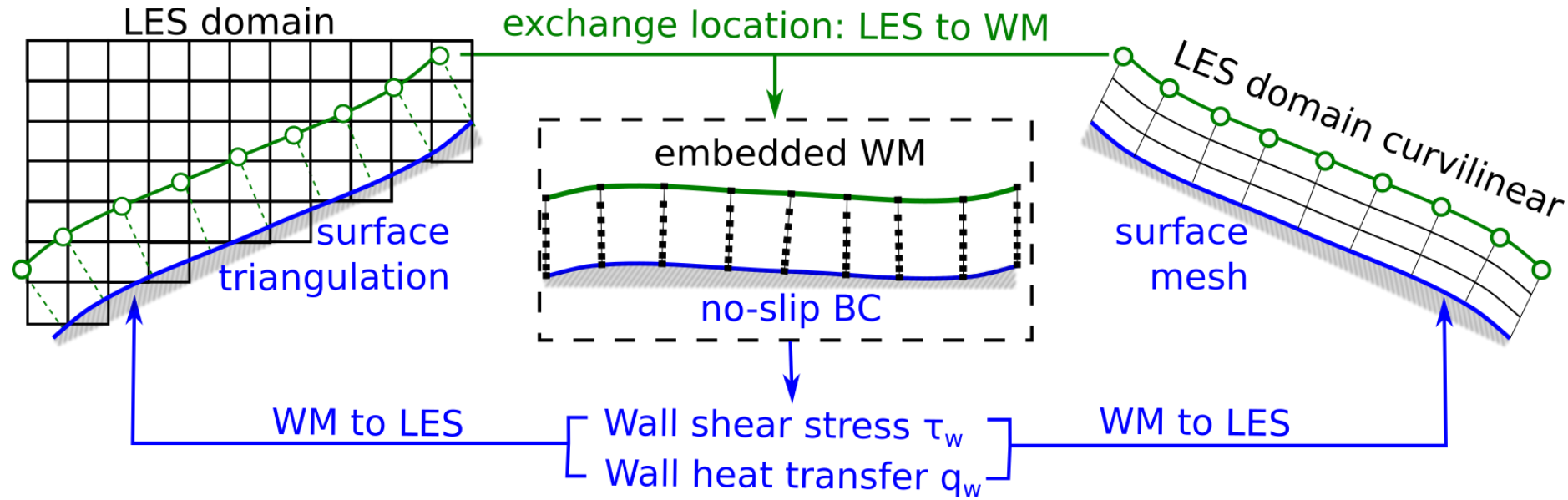
Acknowledgements

- This work was funded by NASA Aeronautics Research Mission Directorate's (ARMD) Transformational Tools and Technologies (T³), Advanced Air Transport Technology (AATT), and Commercial Supersonic Technology (CST) projects.
 - T³ funding has enabled research leading to several modeling and simulation improvements, directly benefitting a variety of NASA programs
- Cetin Kiris for his many contributions to the LAVA Team's success over the years
- Mujeeb Malik for his valuable suggestions and his leadership in T³ RCA Technical Challenge
- Gaetan Kenway, Michael Barad, Abram Rodgers, Victor Sousa, Keshav Sriram, and other LAVA Team members who contributed to this work
- Computer time has been provided by the NASA Advanced Supercomputing (NAS) facility at NASA Ames Research Center



Backup Charts

Wall-Modelled Large Eddy Simulations



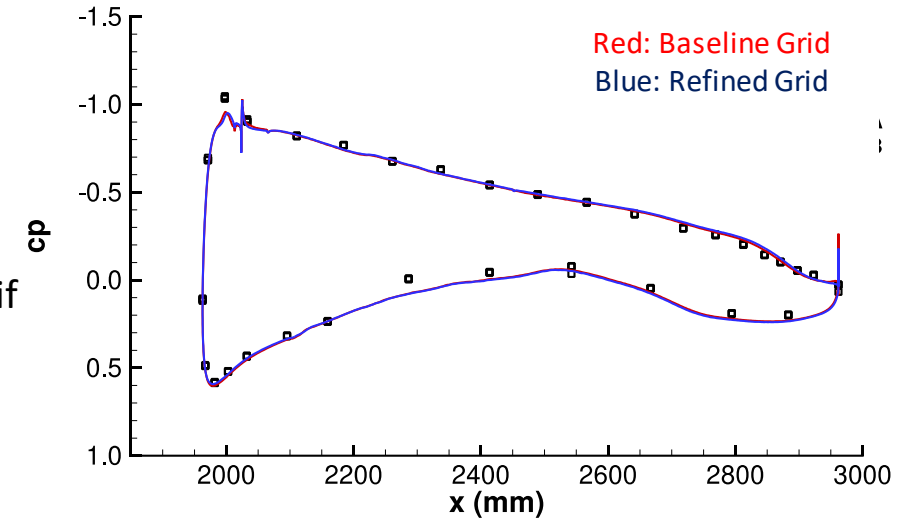
- **Eliminating $y^+ < 1$ constraint** allows for significantly higher streamwise and spanwise resolution for the same computational cost
- Inner-layer (viscous) scales in BL modelled using a **stress-equilibrium assumption**
- Subgrid (subfilter) scales modelled using an **eddy viscosity (dissipative) closure** with some basic properties
- At least **3 potential issues** pertinent to HL-CRM need to be considered:

Wall-Modelled Large Eddy Simulations

Issue 1: How is LES a feasible tool if “grid convergence” requires DNS?

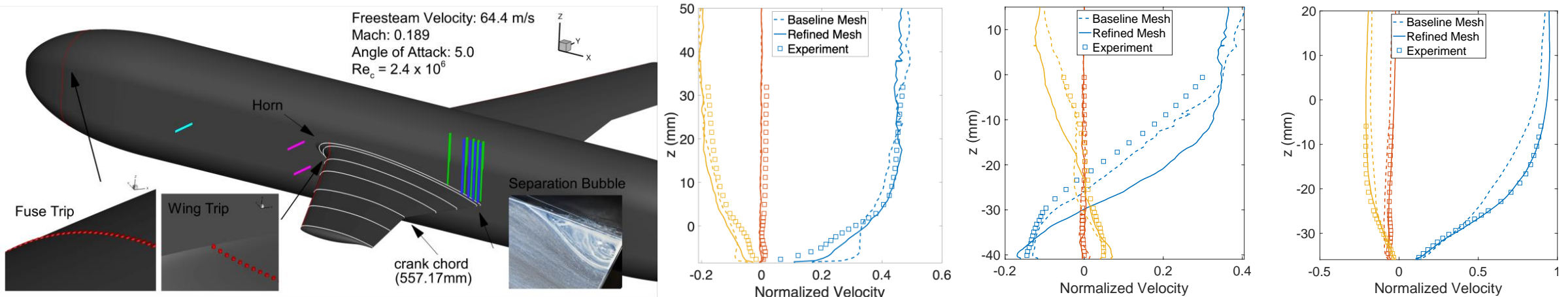
- Meyers & Sagaut (2007) demonstrated non-monotonic convergence of velocity profile for channel flow even for WRLES
- Evidence suggests:
 - Pressure convergences much earlier than velocity profiles (Juncture Flow WMLES)
 - Aerodynamic loads could potentially be obtained within engineering tolerance if “flow topology” is predicted with “adequate accuracy”
- Outcomes of CTR 2018 Summer program (Lehmkuhl et al’s CLmax study) very encouraging

Juncture flow WMLES



Downstream into the corner-flow bubble

Outboard away from root



Wall-Modelled Large Eddy Simulations

Issue 2: How can equilibrium models predict non-equilibrium flows?

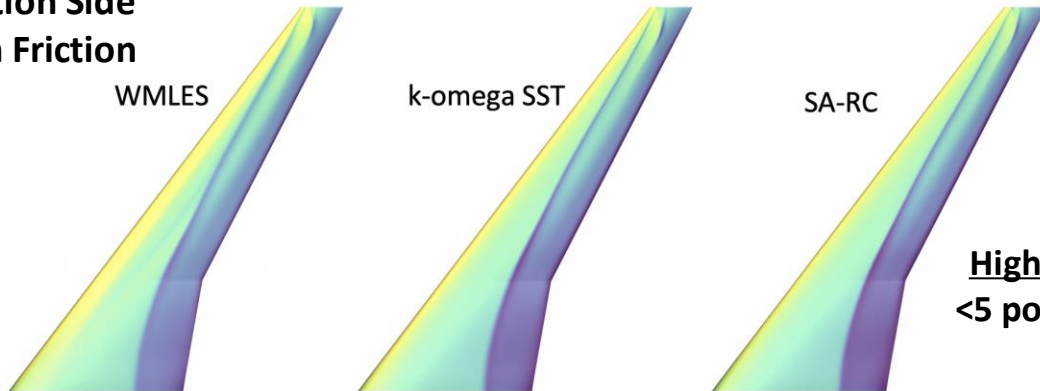
- Coleman et al. (2015) argued for **weak-influence of pressure gradient**
- Main arguments in support of equilibrium modelling:
 - Inner-layer dynamics are much **faster time-scale** than outer-layer dynamics ($\tau \propto \frac{k}{\varepsilon}$)
 - **Convection and pressure gradient in-balance** at $y^+ > 30$ (Hickel et al., 2012): Need to resolve outer-layer non-equilibrium dynamics (low-dissipation, low-grid AR to prevent artificial geometric anisotropy)
 - Errors due to equilibrium modeling show up **most prominently in skin-friction and not in pressure** – but in these situations skin-friction is close to zero anyway (see Park, 2017)
 - Many of the proposed non-equilibrium models are either: a) **inconsistent**, or b) Not easily scalable to complex geometries
- Equilibrium WMLES grid requirements for **smooth-body separation** remains a topic of research
 - Gaussian bump WMLES are worrying – large grid requirements to predict separation accurately; sensitivity reported to subgrid scale closures (Iyer & Malik, 2021; Agarwal et al., 2022)
 - Incipient separation particularly challenging – could be interpreted as error in angle-of-attack in problems such as HL-CRM

Wall-Modelled Large Eddy Simulations

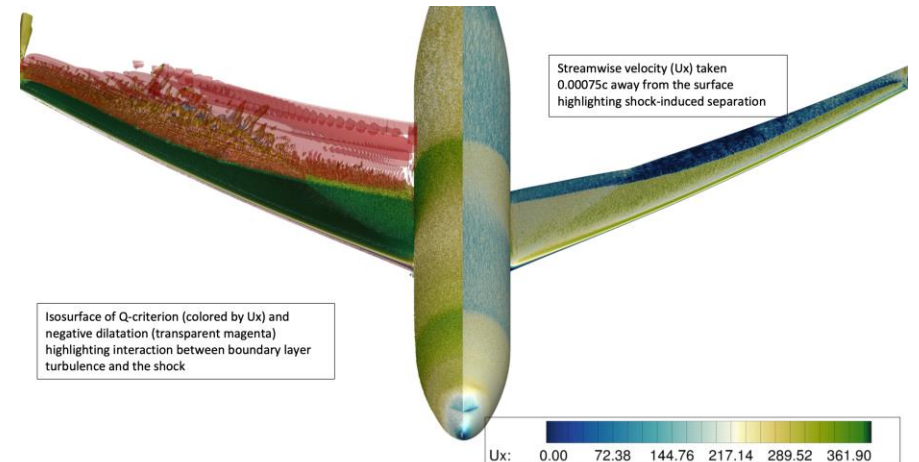
Issue 3: Resolution needed to resolve thin LE boundary layers is a show-stopper.

- Equilibrium attached boundary layers can be predicted correctly with very coarse-grids (5-8 points per δ) : cross-component of Reynolds stresses correct on coarse grids unlike variances
- Evidence suggests that errors damp (as opposed to grow) in favorable pressure gradients: Large errors near leading edge do not significantly propagate downstream
- WMLES on coarse grids seem to predict skin-friction drag accurately (compared to RANS on $y^+ < 1$ grids)

Suction Side Skin Friction



High-Speed CRM wing
<5 points per δ at 10%c
 $y^+ > 80$



- Thin-BLs are likely to be more problematic when they separate: incorrect variance due to coarse-resolution will affect separation prediction – potential cause for concern on outboard portions of the wing (at high-angles of attack), as well as on the flap (shallow separation at low angles of attack)

New Capability: Immersed Boundary WMLES in LAVA



- Uses a **Ghost Cell Method** to impose inviscid boundary conditions at the wall
- **4th order accurate inviscid flux discretization** (order/stencil not changed near walls); 2nd order interpolation for image point probing
- New immersed boundary method developed (*journal manuscript under preparation*):
 - **Complex geometry handling:** Fully consistent ghost cells are used regardless of geometry complexity (sharp corners, thin edges) – required special data structures for ghost cells to take stencil-specific values).
 - **Spurious dilatational and entropic content** : Numerical treatment to address spurious modes without filtering or upwinding near smooth-walls (very relevant for coarse-grid WMLES)
 - **Wall-Stress treatment:** The formulation ensures that the full-wall stress is applied when boundary stress-tensors are rotated in the wall-aligned frame of reference and momentum conservation in this rotated frame is enforced at the walls.
- Stencil based upwinding **only applicable at trapped-cells**: use 3rd order WENO (Jiang & Shu, 2002) interpolation locally

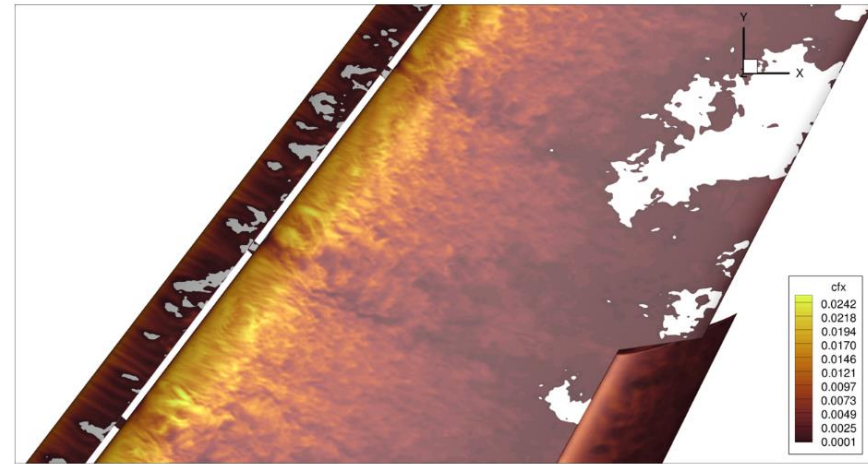
New Capability: Immersed Boundary WMLES in LAVA



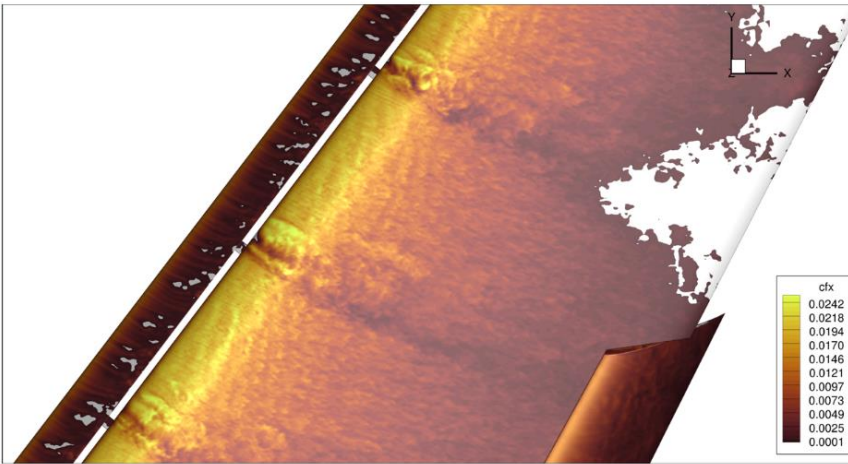
Midboard/Outboard wing at CLmax,
Instantaneous c_{Fx}
Blanked Regions depict $c_{Fx} < 0$

Special emphasis on:

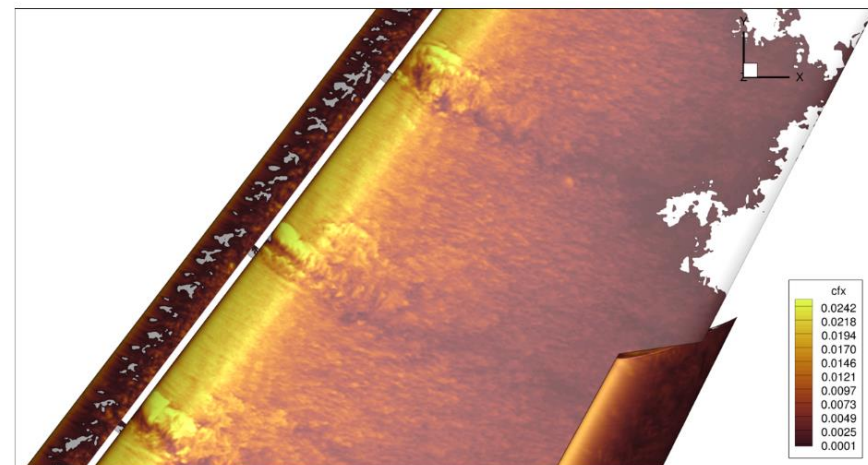
- Avoiding spurious stair-stepping or Cartesian Imprinting
- Numerically transitioned BLs should not have Cartesian-effects
- No tunable artificial “tripping” – flow transitions on its own



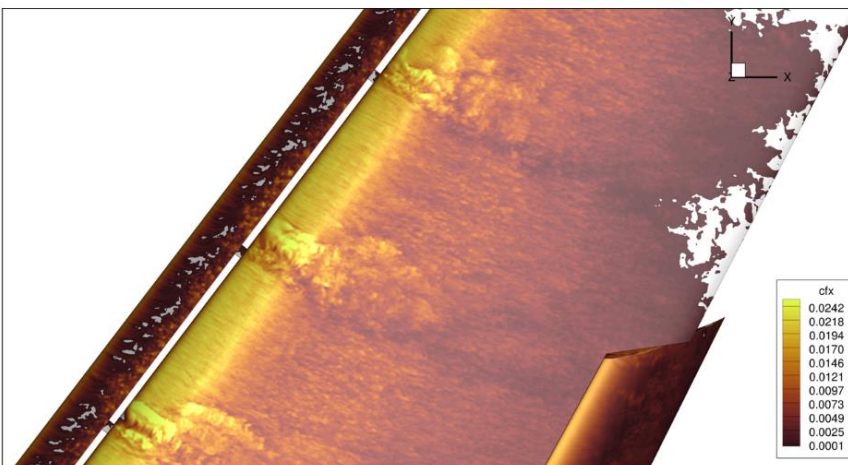
(a) 12mm Grid (100M)



(b) 6mm Grid (450M)



(c) 4mm Grid (1100M)



(d) 3mm Grid (2020M)

Discretization for LAVA WMLES



Curvilinear vs. Cartesian Discretizations

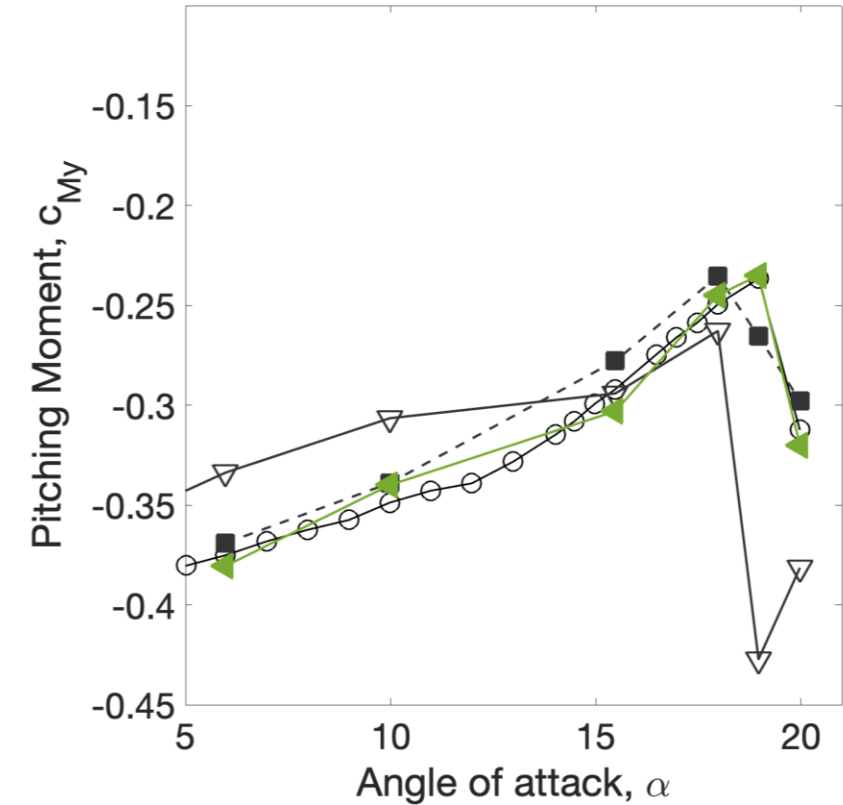
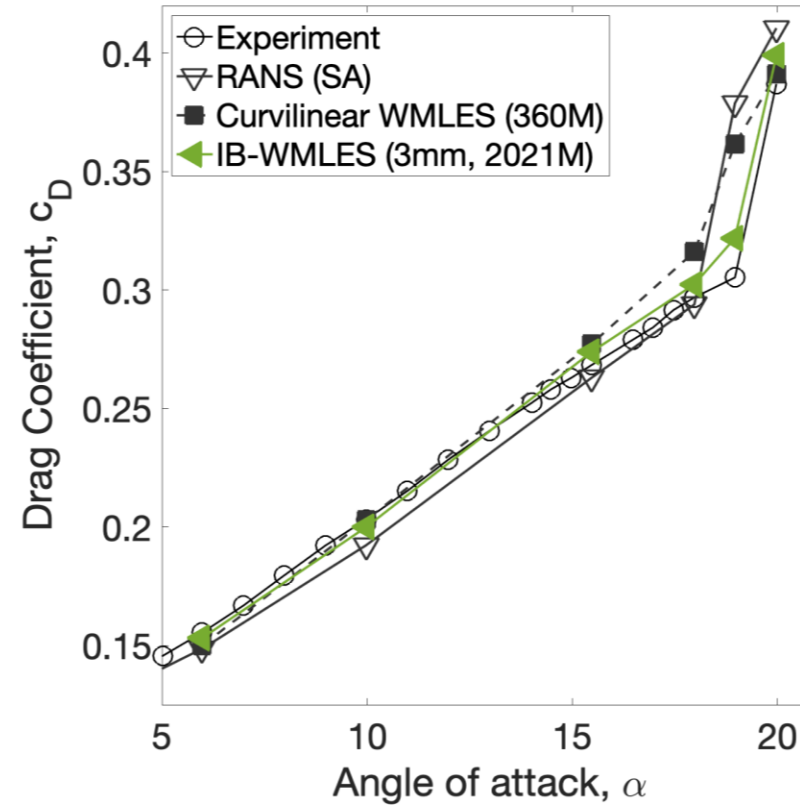
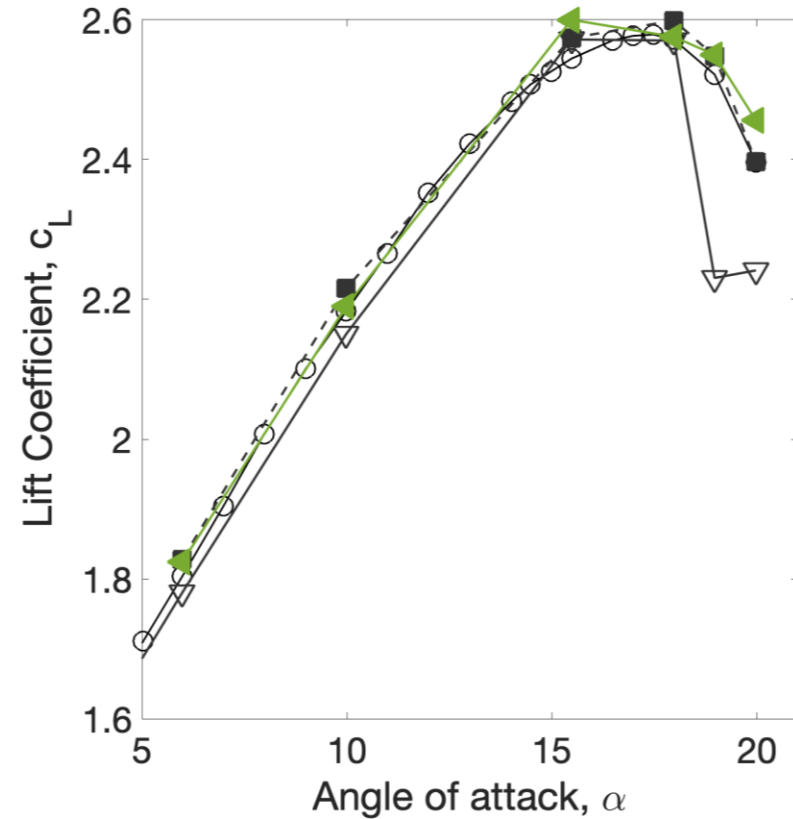
Similarities:

- Constant coefficient Vreman model (little sensitivity observed to model constant at CLmax)
- 2nd order staggered viscous flux discretization
- Localized upwinding (3rd order linear upwind biased interpolation) based on a Ducros-Type sensor
- Explicit Time-stepping using 3rd order RK (similar CFL values)

Differences:

- Curvilinear uses 2nd order derivative of flux; Cartesian uses 4th order derivative of flux (Nonomura et al., 2013)
- Curvilinear uses wall-function by Musker (1979); Cartesian uses a custom blended function (lower cost)
- Curvilinear uses WM exchange at $2\Delta_x$; Cartesian uses WM exchange at $1\Delta_x$ from wall (little sensitivity reported at CLmax)
- When upwinding is active, Curvilinear uses HLL Riemann Solver, Cartesian uses HLLC Riemann Solver (little sensitivity; mostly cost considerations)

In-Tunnel Simulations



[Refer to paper for information on:](#)

1. Initialization procedure (tunnel back-pressure)
2. Tunnel floor BL comparisons with rake data

After interpolation to primary/final grid:

1. Transience washout: 10-20 CTU
2. Statistical averaging: 10-30 CTU ($\alpha < 18^\circ$) and 80 CTU ($\alpha > 18^\circ$)